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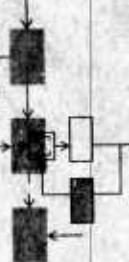
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FINAL REPORT 6873-FR-3
Contract No. AF-33(038)-24007

AUTOMATIC PROGRAMMING of NUMERICALLY CONTROLLED MACHINE TOOLS

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Department of Electrical Engineering

AUTOMATIC PROGRAMMING OF NUMERICALLY
CONTROLLED MACHINE TOOLS

Final Report 6873-FR-3
for period
June 26, 1956 to November 30, 1959

J. E. Ward

January 15, 1960

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ABSTRACT

is reviewed

This report summarizes work done by M. I. T. on the use of digital computers * to transform English-like part descriptions into the detailed numerical data required for numerically controlled manufacturing. The computer programming system which has ^{been} developed is called APT (Automatically Programming Tools) and is an integrated approach to the problem of moving a tool over surfaces independent of the machine tool used. Versions of the system, based on the specification of surfaces by three-dimensional space curves (APT II), and by bounded regions of surfaces (APT III), have been developed. The system has growth potential, since additions and improvements to the input language, calculating routines, and tool-output routines are possible. An industrial version of APT has been under development since 1957 as a joint effort under the APT Project of the Numerical Control Panel of the Aerospace Industries Association. The industrial APT II system, which operates on the IBM 704 computer, provides data for all types of continuous-path millers currently in use. The role of M. I. T. as initial technical coordinator of the AIA joint effort is described, as well as current liaison work.

A summary is also presented on

~~The report also summarizes~~ work in adaptive machine-tool control, automatic feedrate control, curvilinear interpolation, and initial studies on the use of computers as aids to design, which will continue under a new contract. Reference is given in each area to details reported in eleven Interim Engineering Reports, twelve Technical Memoranda, and a seven-volume APT Manual. Included as appendices are reprints of the previous Final Reports on this same contract: 6873-FR-1, "A Numerically Controlled Milling Machine, Final Report on Construction and Initial Operation" Part I, July 30, 1952, and 6873-FR-2, "Design, Development, and Evaluation of a Numerically Controlled Machine Tool" March 15, 1956.

* for transforming
** were developed,

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CHAPTER I

SUMMARY

A. INTRODUCTION

From June, 1956 to November, 1959, the Electronic Systems Laboratory, under the sponsorship of the Air Materiel Command, has undertaken the development of techniques for using digital computers to aid in preparing the mass of detailed data necessary to guide numerically controlled machine tools in sculpturing three-dimensional, high-tolerance parts. This work is a logical extension of the numerical machine tool control development carried out previously under the same contract from February, 1951 to February, 1956.

In total, contract AF33(038)-24007 has run eight years, ten months with numerous amendments and extensions as the work has progressed. The present document is the final report on the contract and summarizes the work done in the three and one-half years since the previous report, which is reproduced for reference in an appendix.*

It is important to note that completion of this contract should not be taken as an indication that the field of automatic programming for numerical control is closed to further research. A more realistic evaluation would be that the significant developments of the past few years form a solid foundation of enhanced understanding and basic techniques upon which further research as well as development can be based. Under a new contract, the Electronic Systems Laboratory will continue liaison work with the industrial group putting these developments into practice. Also, the preliminary studies on computer-aided design

* The final report on Design, Development, and Evaluation of a Numerically Controlled Milling Machine, dated March 15, 1956, is reproduced in Appendix A; and the Final Report on Construction and Initial Operation, Part I, dated July 30, 1952 is reproduced in Appendix B.

reported herein will be expanded into a full-scale investigation. By this combined effort, it is felt that the long-range goal of automatic control of the total manufacturing process can most effectively be realized.

B. BACKGROUND FOR PRESENT PROJECT ACTIVITIES

The Electronic Systems Laboratory, (formerly Servomechanisms Laboratory) M. I. T., has played a leading role in the development of numerical control for a number of years.* In 1952 the Laboratory group under the direction of W. M. Pease, J. O. McDonough and A. K. Susskind demonstrated the first numerically controlled milling machine; between 1952 and 1954 the first set of digital computer subroutines for cutter-path calculations were developed for the M. I. T. Whirlwind Computer by John H. Runyon; and in 1955, under sponsorship of this laboratory, Arnold Siegel of the M. I. T. Digital Computer Laboratory demonstrated on Whirlwind the first pilot model two-dimensional automatic programming system for numerical control. In June of 1956 the Air Materiel Command contract, under which previous work had been performed, was reoriented for research into general automatic programming techniques for three- and five-axis continuous path milling machines.

C. THE PROGRAMMING PROBLEM IN NUMERICAL CONTROL

As may be recalled from earlier reports on the design, construction, and utilization of numerical control,* a numerically controlled machine tool is one to which have been added servomechanisms and electronic control circuitry which enable the tool to respond to numerically coded instructions on some suitable control medium, such as punched tape. The electrical circuitry at the tool may respond directly to numerical data, or alternatively a remote machine tool "director" may be used to convert numerical data to continuous analog signals which are recorded on magnetic tape for actual control of machining operations by simple analog playback equipment. In either case, the preparation of the numerical instructions which specify the machine motions required to produce a particular part is called programming the machine tool, or part programming.

* Please see Appendices A and B.

The preparation of part programs by manual methods is an extremely tedious process, since the end points of perhaps thousands of straight-line (or in some cases parabolic) cuts must be calculated on the basis of the desired tolerance and finish for the part. This process, if done manually, is so complicated, time consuming, and subject to errors that numerical control would hardly be feasible. The solution to the part programming problem is to use digital computers to assist the human part programmer in developing the required numerical data. This was first done by writing computer sub-routines which could calculate the required straight-line approximations to common curves, such as circles and parabolas, when the part programmer supplied the necessary parameters and the starting and ending points where the curves joined other surfaces. One drawback to this approach was that the part programmer still had to calculate the intersections of the curves and lines which bounded a part, and was thus still involved in considerable detail. Also, he had to be intimately familiar with computer coding since in essence a computer program had to be written for each part.

In this sense, using a digital computer to part program is little different from other types of computer calculations--a primary problem is the preparation of the computer program. Computer programmers have learned how to greatly reduce the difficulty of computer use by developing automatic programming techniques which remove the computer user from direct contact with the detailed machine code and permit him to work with broader and more meaningful statements and instructions. This is done by writing a very sophisticated program for the computer which has the ability to interpret statements about a class of problems made in a mnemonic "language" different from the machine code, check the statements for errors or inconsistencies, and then perform the required functions. An example of such a program is the FORTRAN system for the IBM 704 computer which is designed to solve equations stated to it in almost the normal mathematical form, thus making it possible for people unfamiliar with computer coding to solve problems. While preparation of such a program is very difficult and time consuming, the work need only be done once, and all subsequent users are benefited because their job is made much easier. In fact, the current widespread use of computers has been made possible by these techniques.

Automatic programming for machine tools then is a technique borrowed from the digital computer art in which the machining instruction are not prepared in detailed numerical form, but in terms of an English-like language which can be "understood" by a computer. In this language, the part programmer may conveniently define the curves or surfaces which bound the part and specify the sequence of tool motions over these curves and surfaces. The language permits curves to be defined in terms of other curves, for example the circular arc for a corner fillet can be described simply by giving its radius and saying that it is tangent to the two lines forming the corner. This is in contrast to the original computer part programming where the fillet intersections had to be computed and specified. The computer output is directly in the coded form required for the machine tool director electronics. Automatic programming thus permits the difficult mathematical computations associated with the use of numerical control to be performed automatically by the computer so that the job of the human part programmer is greatly simplified.

D. PROJECT ACTIVITIES

At the close of the contractual period covered by the previous Final Report in March, 1956, a rudimentary automatic programming system with a mnemonic language for calculating two-dimensional parts had been demonstrated by Arnold Siegel. The new work which started in June, 1956 was intended to expand and adapt this approach to provide an automatic programming system for three-dimensional parts and for tools with more than three degrees of motion. It was soon found, however, that the calculating portions of the Siegel approach could not be expanded into the desired system, and that it was necessary to devise a new approach. The new organization which has been developed for automatic programming systems is called APT, which is an abbreviation for Automatically Programmed Tools.

Actually, the APT system is not a single system as the name implies, but is a framework to which additional features can be added in the future to provide greater and greater capabilities. Two different APT systems, APT II based on space curves and APT III based on space regions, have already been developed. The APT systems are designed to permit the production of complex metal parts efficiently and reliably through the combination of computer data processing and numerically controlled machine tools, and show promise for providing in the near future a means for realizing

the full potential of numerical control. Chapter II of this report contains a brief description of the project's activities in developing the APT system concept, the APT II and APT III systems, and other work in numerical control technology, such as studies in automatic feedrate control, higher order interpolation for machine-tool directors, and adaptive controls. It also describes initial work in a new area which will continue under a new contract, AF-33(600)-40604, which started December 1, 1959. This new area is that of computer-aided design, which in combination with numerical control and the APT systems is expected to eventually lead to completely automatic manufacturing.

The APT concept, originated at the Laboratory, has been under development for industry-wide use since April, 1957 in a cooperative programming venture sponsored by the Aerospace Industries Association (AIA).* Details of the project's role in initial technical direction of the AIA effort and in continued liaison may be found in Chapter III of this report.

The work of the project for this period has been documented in eleven interim engineering reports, forty-two monthly progress letters, a special seven-volume report on the use and application of the industrial APT system, and twelve technical memoranda. Also, information has been disseminated via papers presented at nine technical conferences and one press conference, a half-hour television film, computer card decks and instructions distributed to industry, working meetings at M. I. T., and regular meetings of the Numerical Control Panel of the AIA. Complete references to all publications may be found in Chapter IV.

E. BREAKDOWN OF PROJECT EFFORT

In carrying out its research and development activities during the past 42 months the project has operated under five general tasks, although not all at the same time. Approximately 22 man years of effort were applied to these tasks, which are listed below with an estimated percentage of the total effort:

1. Design, development and testing of prototype APT systems. (39%)
2. Technical coordination of the initial version of the industrial APT II system (33%)

* Then called the Aircraft Industries Association

3. Information dissemination to aid industrial understanding in utilization of numerical control and computer-tool systems (8%)
4. Development of special computer utilization techniques to support the systems work, and academic thesis studies on selected areas in numerical control technology. (13%)
5. Preliminary study of the feasibility of using automatic programming for the preparation of design information. (7%)

CHAPTER II

RESEARCH AND DEVELOPMENT OF NUMERICAL CONTROL AT THE ELECTRONIC SYSTEMS LABORATORY

Project work during the 42-month period covered by this report fell roughly into five areas, as listed in the summary section of the previous chapter. The two main efforts were centered on design, development, and testing of prototype APT systems and extensive liaison work with the AlA. The rest of the project effort, somewhat less than a third of the manpower, was used in the remaining three areas of work, which included research in support of the two main items above, and in studies directed toward other areas in numerical control technology. All of this work, except for the AlA liaison, is described in this chapter. The AlA liaison work is described in Chapter III.

This chapter is an account of the research and development work in APT system prototypes on the Whirlwind and IBM 704 computers at M. I. T.; development of oscilloscope plot and group control programs for APT; related programming studies in English translation, iterative procedures, and list techniques; thesis studies of adaptive controls for tracer milling, automatic feedrate control for numerically controlled tools, and incremental computer techniques for higher-order interpolation in tool directors; and a study of the feasibility of using man-computer systems extensively in the design process.

A. DISCUSSION OF APT SYSTEM OBJECTIVES

An APT system for programming numerically controlled machine tools must be capable of receiving a description of the desired part to be machined in some human-like language, and of generating an appropriate machine-tool code which instructs a machine tool to make the desired part. Such a system is usually subdivided into three major parts -- a translator, a calculator, and a post-processor. The translator receives the original part program in a human-like language and breaks it down into specific instructions (having a more rigid and detailed format) which instruct the computer to carry out its functions. In response to the translator output

the computer of the Automatically Programmed Tool (APT) system generates a sequence of tool centers which specify the path to be followed by the cutter of the machine tool for the production of the desired part. The post-processor uses the tool centers calculated by the APT computer together with information about feedrates, permissible accelerations, etc., to produce a code recognized as instructions by the numerical director of the particular machine tool to be used to cut the desired part.

In the project work the three parts of the APT system "computer" have been simulated by appropriate programming for a general purpose digital computer, as shown in Fig. II-1. In this figure, the three general functions of translation, calculation, and post-processing are indicated by the "dimension" arrows along the left-hand margin. Each of these general functions is, of course, broken down into more detailed tasks. At some time in the future, after the necessary programs for numerical control have been designed and tested on the general purpose computer, the simulated APT system could form a basis for the logical design of a special purpose computer especially tailored to the purposes of numerical control. Such a computer would have a great advantage in speed over present simulated "APT computers."

The philosophy followed in the APT development is to find a method for determining the cutter motions to generate any desired curve or surface, without having the method depend on the curves or surfaces involved. If the method were to depend on the individual curves or surfaces, the system of programs would require a separate calculating subroutine for each one and would thus be exceedingly large and complicated. Changes and additions would be difficult because as each new subroutine was added, the control or executive routines would have to be modified, and the whole system of programs would be in a state of constant flux. Also, considerable redundancy in programs and storage would be present, because many surface subroutines would differ only in minor ways. After initial research, it was found that there are two properties, the unit normal vector and the directed distance, which are common to all surfaces, in terms of which a common calculating program could be developed to handle all surfaces, provided that two subroutines for evaluating these properties were available for each surface type. Thus, additions of new surfaces do not require new control routines, but only additions to the unit-normal and directed-distance

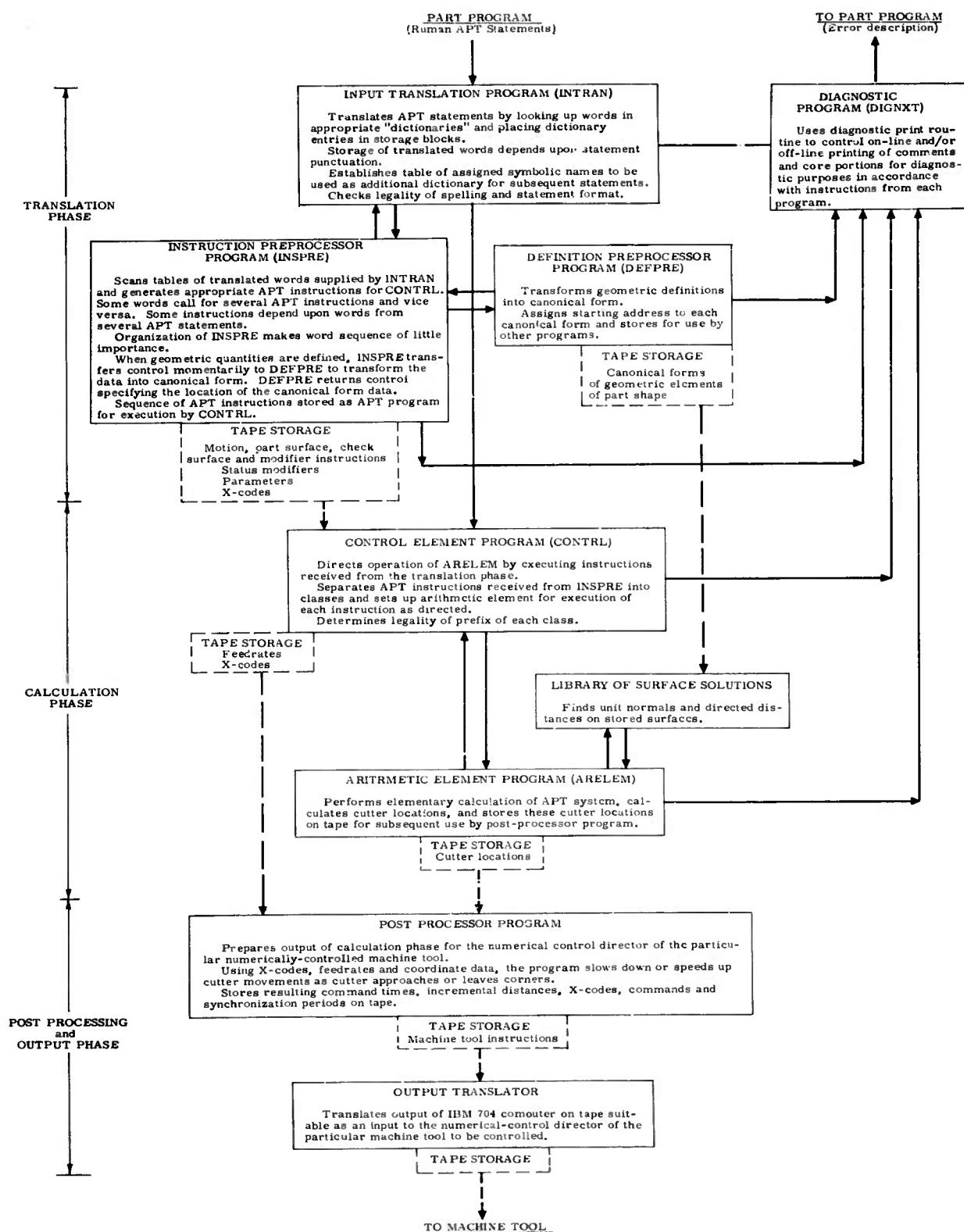


Fig. II-1 Functions of APT System Programs

subroutine library. Also in this system, curves in space may be defined as the intersections of surfaces, and it is possible to reduce greatly the number of necessary subroutines for curve definition because the subroutines for two surfaces used in different relative orientations can generate a large number of different curves.

The APT computer is capable of generating by means of subroutines the two required properties for any particular surface, and in general, these two properties are adequate for the description of all operations with respect to surfaces. The unit normal vector defines the tangent plane at the point of tangency and this plane is an approximation of the surface around the point of tangency. The directed distance subroutine calculates the the distance to the surface from any point in space and along a prescribed direction. In addition to other uses, the directed distance is employed to determine the extent to which the tangent plane approximation is within the limits of the allowable tolerance. The inputs to and outputs from these routines, and pictorial definitions of the two properties are shown in Fig. II-2.

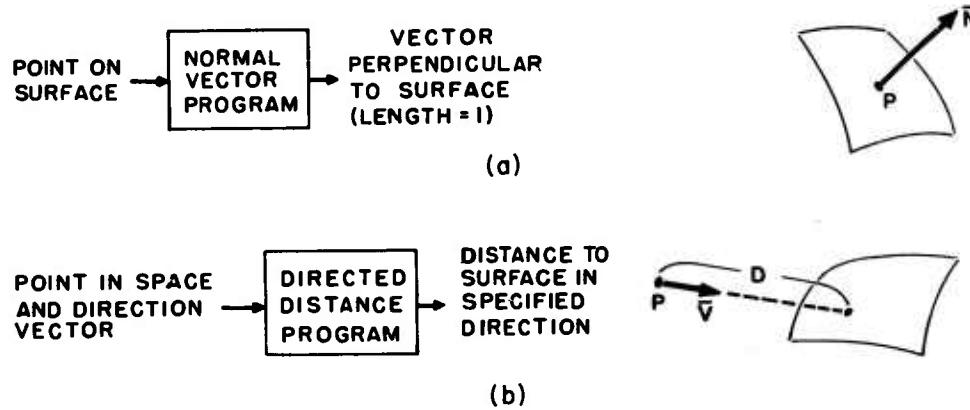


Fig. II-2 Concepts of Normal Vector and Directed Distance

It is usually most efficient to write special normal vector and directed distance subroutines for each type of surface, but it is also possible to devise general-purpose iterative normal vector and directed distance programs so that subroutines for functional definition of the surface itself are all that is required. Therefore, as long as a surface can be defined by means of a program, normal vectors and directed distances can be computed even though special analyses for them may not be known.

It has been found that these special descriptive properties of surfaces supply all of the information needed for constructing mechanistic, systematized solutions to the geometric problems which arise in numerical control programming. The normal vector program provides information about the orientation of the surface, and since the tangent plane to the surface at that point is determined by the set of all vectors perpendicular to the normal vector, it is possible to "move" on the surface approximately by moving along a selected tangent vector. The directed distance program is very useful since if the distance to the surface is known in a specified direction, it is possible to "move" directly to the surface. The combination of normal vector and directed distance programs, therefore, allows approximate motions to be corrected exactly, so that motion over arbitrary surfaces is possible without any build-up of errors. Normal vector programs are also useful for calculating curvatures of surfaces, etc., and directed distance programs can be used in many ways to control step-by-step iterative calculations with respect to surfaces, since it is possible to "look ahead" and determine whether a given condition has been met.

Using the fundamental geometric properties of normal vectors and directed distances, single general purpose programs have been written which form the skeleton for a program which will solve the tool motion problem for any particular surface. It is only necessary to flesh out the skeleton by selecting the appropriate normal vector and directed distance subroutines and inserting them into the appropriate locations in the general skeleton program. Thus the concept of a systematized solution has greatly simplified the geometric part of the numerical control programming problem. Notice that the subroutine library has not been completely eliminated, (normal vector and directed distance subroutines are still required for each type of surface), but it certainly has been reduced in complexity. The chaotic lack of structure of the usual large subroutine library has been replaced by the serenity of a homogeneous, small library with fixed skeleton programs in which all of the difficult problems have been solved once and for all. An ordered and controlled growth of the APT system capabilities can be envisioned since it is easy to add new surface types to the simple library.

B. APT IS MORE THAN A SINGLE SYSTEM

Up to this point, the idea of an automatically programmed tool system has been used in a more or less loosely defined way to refer to the automatic generation by a digital computer of machining instructions to operate a numerically controlled tool. In this usage the computer is programmed by geometric information typed on a keypunch or typewriter in a form convenient for the part programmer. This geometric information describes the part to be made, the cutter to be used, the tolerance to which the part is to be cut, and the machine feed-rate. The task of the computer is to perform all necessary calculations in the explicit and detailed sequence of hundreds or possibly thousands of machining instructions necessary to move the tool. However, there are various gradations or performance levels in this type of operation.

During the course of the project work since 1956, several definitions have been evolved to classify various kinds of APT systems. These classifications have been largely based on the kind of information which is given as input from the part programmer to the computer. At the start of this phase of the project work, the designation "APT I" was given to all programming systems in which actual cut vectors must be specified by the part programmer. This category also includes the computer programming systems in which the part programmer must calculate and specify intersection points of curves to be calculated by the computer.

In the hierarchy of the APT system, the next level above the APT I systems described above is the APT II system in which the part description and the machining instructions are based on space curves. As a tool moves over a three-dimensional work surface, it moves along a series of connected space curves. Actually, most machine tool directors perform linear interpolation and these curves are approximated by moving the tool in a series of straight line segments. Thus the tool motion over a surface such as in air foil may be thought of as a series of curves, each made up from many small straight line motions. In the APT II system each space curve along which the tool must move is generated in the computer by the intersection of surfaces. The surface types and their relative orientations can be specified to the computer in a convenient input language and the programmer can schedule operations by a sequence of cutting instructions referring to the proper surfaces. Note that in order to machine an area by this system,

the part programmer must schedule the tool along a series of zig-zag curves, or along a spiral curve in such a manner as to space properly the cuts to machine the entire surface. The recognition that such a process requires considerable thought and work on the part of the programmer, and more instructions in the part program than are actually necessary, led to the development of the next system in the APT hierarchy, the APT III or region programming system.

Whereas the APT II system requires the specification of a space curve for each tool motion over a surface to be cut, the APT III region programming system requires only specification of the surface and its boundaries. The calculating portions of the APT III simulated computer automatically determine the sequence of tool cuts required to finish the surface region inside the specified boundaries. Thus the work of the part programmer and the number of input instructions to the computer is greatly reduced. However, the APT III system requires more sophisticated input translation routines to "understand" surface definitions and machining instructions given with respect to them.

A representation of these "levels" of APT systems is shown in Fig. II-3. It will be noted that each higher system of programs builds on those of the lower levels, thus the levels are not independent but may be thought of as stages in an evolving system, with future developments left unspecified.

At the time the industrial joint programming effort was started under the auspices of the Aero-Space Industries Association, the development of the APT II type of system had progressed at M. I. T. to the point of practicability, whereas the APT III developments were still in the research stage. Thus, it was decided that the initial industrial effort should be to develop an APT II type of system, with the APT III as a goal for a later time. The APT II system permits machining of any three-dimensional part, but requires that the part programmer describe the part in terms of space curves. Improvement of the industrial APT system to handle three-dimensional problems more conveniently in the input language and eventually to incorporate region programming rather than programming by curves will come about as a process of gradual evolution. The programs are designed to permit such additions and changes.

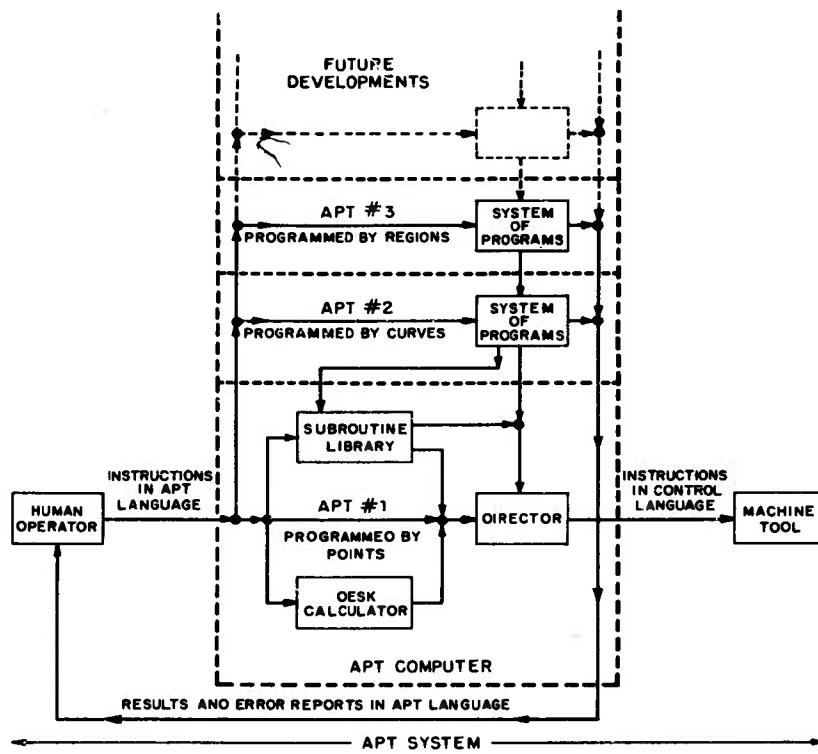


Fig. II-3 The APT System Concept

C. WHIRLWIND PROTOTYPES FOR APT

In performing initial programming research on the APT systems, the Electronic Systems Laboratory used the M. I. T. Whirlwind computer which also had been used previously by Arnold Seigel for his earlier automatic programming work. Program work during 1956 and early 1957 was concentrated on the APT II system prototype. In early 1957, work was also started on the calculating portion of an APT III system. In all of this work, mathematical formulations and programming were first concentrated on the calculating portions of the systems, and these were tested with simulated data inputs to replace those that would normally come from the input translation and definition preprocessor programs. Although the Whirlwind programs never reached full part-programming capability, as will be explained in the next paragraph, the APT II system on Whirlwind had a more complete control element

than the APT III system. Final Whirlwind experiments before the computer was dismantled in May, 1959 involved a merging of the APT II and APT III programs so that the APT II system could be used to calculate the boundary cuts for the APT III system. One test part successfully calculated with APT III is shown in the next section.

The Whirlwind-APT systems may be looked upon as the prototype for the industrial APT II system which has been developed for the IBM 704 computer by the Aero-Space Industries group with M. I. T. guidance (see Chapter III). Since portions of the Whirlwind-APT II system had already been in operation when the joint program started, many of the ideas were proved out and were directly useable. However, some APT II ideas were first developed on the IBM 704. The reason for this is that the AIA effort came along at a time when the Whirlwind systems were not yet completed, and effort that would normally have been put on the completion of the Whirlwind programs was instead put on the similar portions of the industrial APT II system. Thus the Whirlwind system never achieved full capability for part programming, primarily because of uncompleted portions in the input programs. Features and performance of the Whirlwind APT II and APT III systems, and their integration into a common system, have been fully covered in the Interim Reports of the project and will not be treated here. However, examples of Whirlwind-APT II and APT III test parts machined on the M. I. T. Numerically Controlled Milling Machine (see Appendices A and B) and the associated part programs are presented in the next section to illustrate the philosophical difference between APT II and APT III.

D. EXAMPLES OF APT II AND APT III PARTS AND PROGRAMMING

This brief resume of APT II and APT III programming has been included to indicate the basic part-programming characteristics of the two systems, and is not intended to provide definitive descriptions. Complete details on the APT II and APT III systems, rules for part programming, discussion of the calculation and language translation problems, and the results of many more test cases are contained in the interim reports and the APT Documentation.

1. A Whirlwind APT II Two-Dimensional Part

Figure II-4 shows a very simple two-dimensional part known as the "teardrop." The sequence of tool motions from the "set point" with coordinates $x = 1$, $y = 1$ to the work, counter clockwise around the part, and back to the set point are indicated in the figure. The Whirlwind APT II

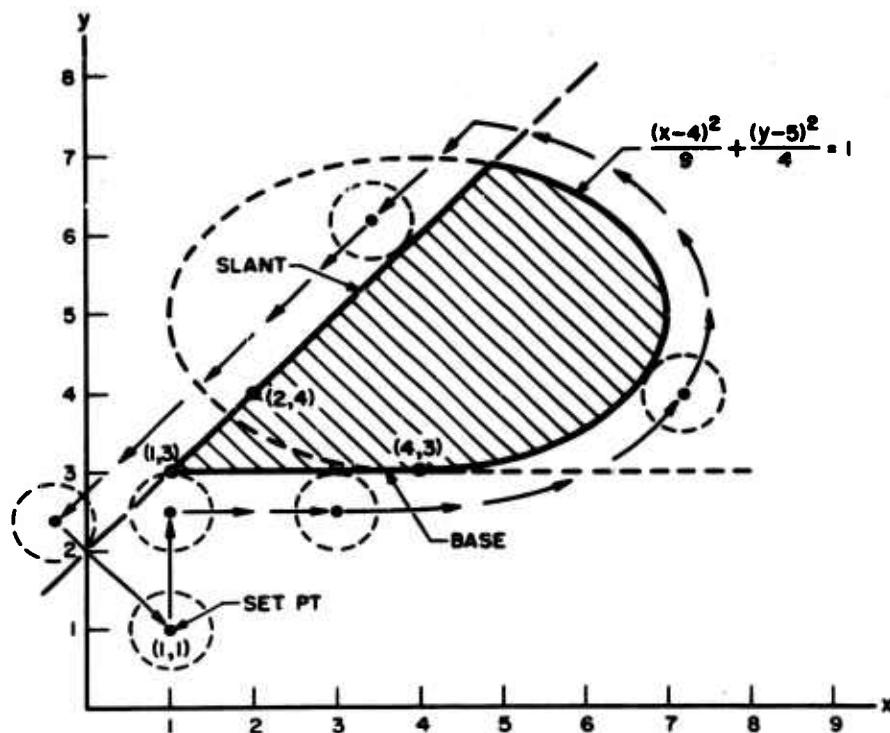


Fig. II-4 Part Programmers Drawing for Teardrop

part program to cut this part is shown below, and it is seen that the part programmer can "talk" the tool around the work piece without having to calculate the intersections of the curves which bound the part. The part programmer also does not have to be concerned with cutter offset calculations since they are automatically performed. In the part program, the comments in small type to the right of the vertical lines have been added for clarity in this discussion and were not part of the actual program.

| <u>Part Program</u> | <u>Comments</u> |
|---|---|
| PS IS, PLANE/0, 0, 1, 0 | Description of part surface |
| BALTL/1 | Ball tool with 1" radius |
| TOLER/.005 | Cutting tolerance |
| FEDRAT/7.5 | Tool Feedrate |
| 2DCALC, ONSPIN, ONKUL | Set program for two-dimensional curves, turn on tool spindle and coolant |
| SETPT = FROM, POINT/1, 0, 0 | Define set point |
| INDIR/1, 3, 0 | Direction of initial tool motion |
| BASE = GO TO, LINE/1, 3, 0, 4, 3, 0 | Define BASE line by two points |
| TL RGT, GO RGT/BASE | Go right on BASE line, with tool to right of work |
| GO FWD, ELIPS/4, 5, 3, .33333, 0, 0, 0, .5, 0 | When BASE line intercepts ellipse, follow ellipse keeping tool on right |
| LINE 1 = LINE/2, 4, 0, 1, 3, 0 | Define LINE 1 by two points |
| GO LFT/LINE1, PAST, BASE | When ellipse intercepts LINE 1, follow it with tool on right of work until tool has gone past BASE line |
| GO TO/SETPT | Return to set point |
| OFKUL, OFSPIN, END, FINI | Turn off coolant and spindle, stop tool director, stop APT program |

2. Three-Dimensional Work with APT II

To indicate how APT II is used to cut three-dimensional surfaces, an example has been drawn from the industrial APT II system for the IBM 704 computer. Figure II-5 shows the cuts programmed on a hyperbolic paraboloid or saddle surface which forms the pocket in an ashtray, developed as a demonstration part. Figure II-6 is a picture of the pocket which shows the actual cuts. The portion of the 704 APT II part program used to machine this pocket, with comments added, is shown below.

| <u>Part Program</u> | <u>Comments</u> |
|--|--|
| • | |
| • | |
| • | |
| ELIPS = ELLIPS/ +1.5, -.662275, +0., + .666666, +0., +0., +0., +.8, +0. | Define outer ellipse in pocket |
| PTC = POINT/ +1.5, -.662275, +0. | Define point below center of pocket |
| LINE 4 = LINE/PTC, AT ANGL, +90. | Define reference line |
| HP = HYPAR/ +1.5, -.662275, +.475, +0., +.75, +0., +0., +0., -5.33333, +1., +0., +0. | Description of hyperbolic-paraboloid surface |
| GO TO/ +1., -.662275, +.13 | Move tool from point U to point V (both above work) |
| TOLER/.01 | Cutting tolerance (outside) |
| FEDRAT/ + 7.5 | Tool feed rate |
| GO TO/ +.5, -.662275, +.13 | Plunge to point W |
| 3D CALC | Set routines for 3-dimensional surface |
| PS IS/HP | Part surface definition |
| TL ON | No tool offset |
| FAR, 2, GO LFT/ELIPS | Go CCW around curve defined by intersection of outer elliptical cylinder with HP to 3rd intersection with LINE 4 (point X) |
| GO LFT/LINE 4 | Move along LINE 4 and HP surface to next smaller ellipse |
| FAR, 2, GO RGT, ELLIPS/ +1.5, -.662275, +0., +1.2, +0., +0., +0., +1.6, +0. | Go CCW around next ellipse until 2nd intersection with LINE 4 |
| GO LFT/LINE 4 | Move to ellipse No. 3 |
| FAR, 2, GO RGT, ELLIPS/ + 1.5, -.662275, +0., +1.5, +0., +0., +0., +2., +0. | Traverse ellipse No. 3 |
| GO LFT/LINE 4 | Move to ellipse No. 4 |

| <u>Part Program</u> | <u>Comments</u> |
|--|---|
| FAR, 2, GO RGT, ELLIPS/+1.5, -.662275, +0., +2.0, +0., +0., +0., +0., + 2.66666, +0. | Traverse ellipse No. 4 |
| GO LFT/LINE 4 | Move to ellipse No. 5 |
| FAR, 2, GO RGT, ELLIPS/+1.5, -.662275, +0., +3.0, +0., +0., +0.. +4., +0. | Traverse ellipse No. 5 |
| GO LFT/LINE 4, TO, ELIPS | Move tool across center along HP and LINE 4 to point Y on outer ellipse (ELIPS) |
| FEDRAT/+ 10 | Change feedrate |
| GO DLTA/+ 0., +0., +.75 GO TO/-1.75, +.7259875, +1. • • • | Move tool up and away from work (point Z) |

It may be noted in the above program that the part programmer was able to specify three-dimensional cuts defined by the intersection of an elliptical cylinder with the hyperbolic paraboloid surface, but that in order to machine the entire surface, he had to index the cutter through a series of such cuts, each time specifying a smaller ellipse until the surface was completely machined. This emphasizes the fact that in APT II, the programmer can think only in terms of cuts along individual space curves.

3. A Whirlwind APT III Three-Dimensional Part

An example of a part cut with the Whirlwind APT III system is shown in Fig. II-7. This part is an elliptical paraboloid which was purposely programmed with a rather coarse tolerance in order to show the cut vectors. Although an input language comparable to those shown above for APT II was not available for the Whirlwind APT III, a hypothetical part program is shown below. Actually, the equivalent of this program,

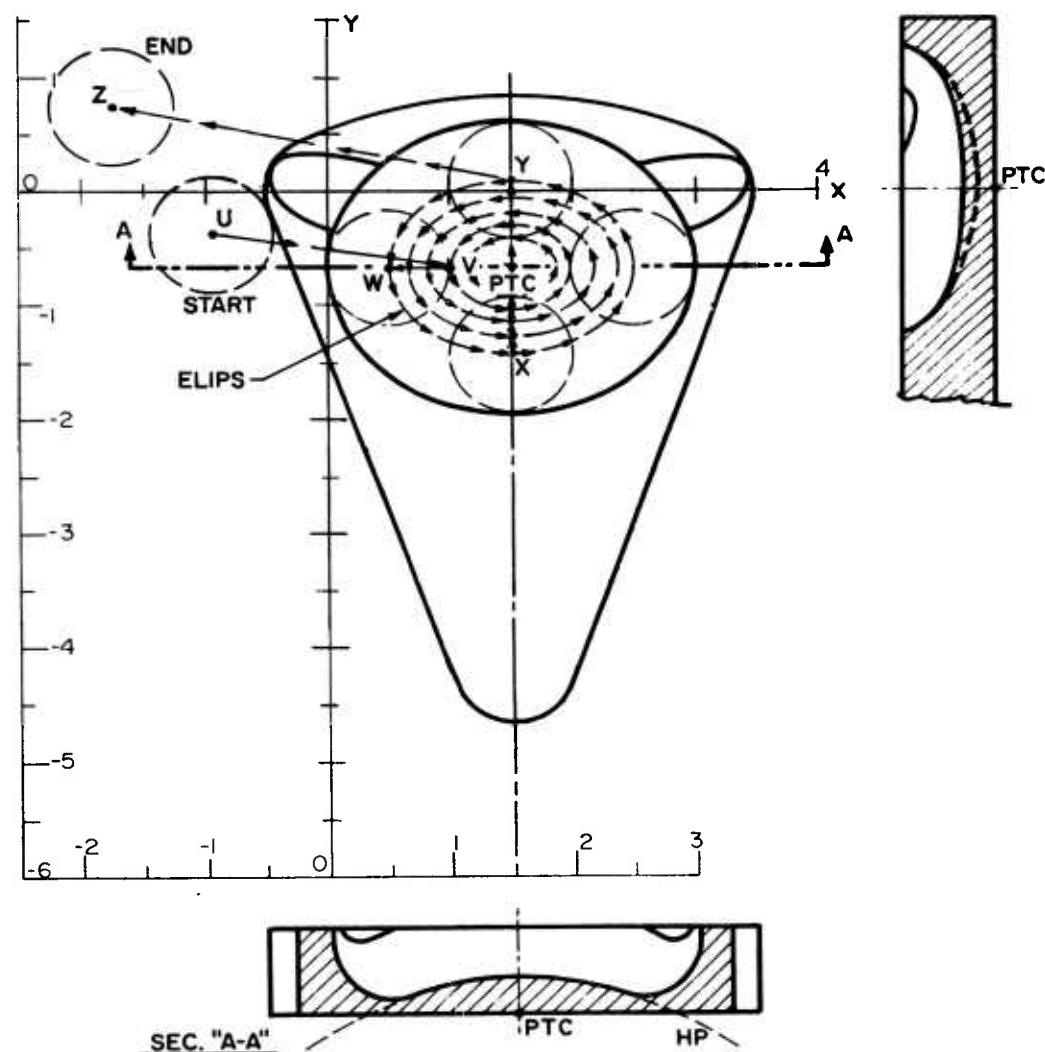


Fig. 11-5 Part Programmers Drawing for Hyperbolic Paraboloid Pocket

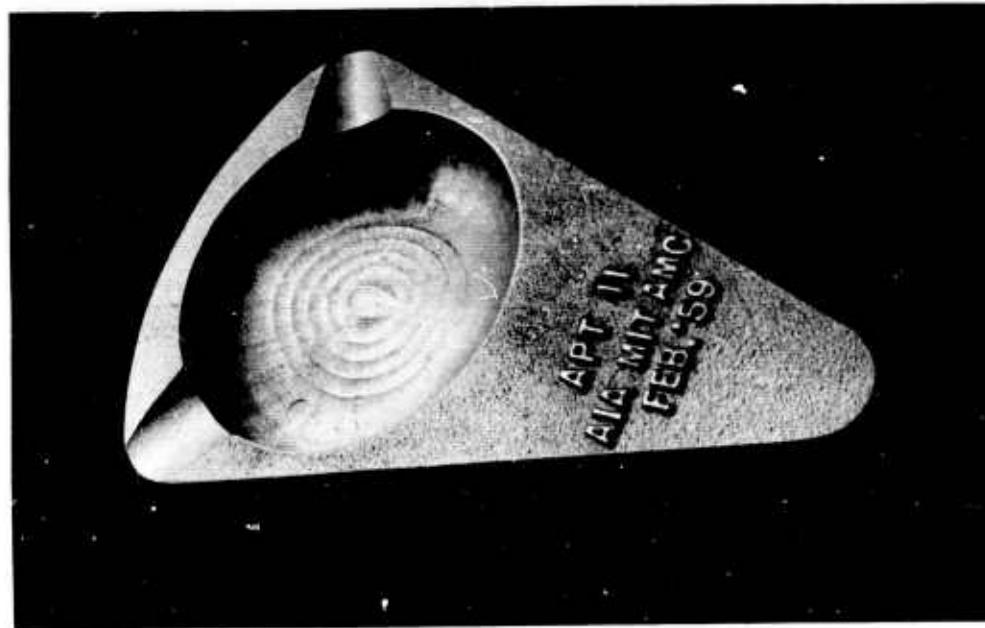


Fig. II-6 Hyperbolic Paraboloid Pocket Cut with APT II

which is hypothetical only in the language used, was entered into the Whirlwind APT III program in binary form. Again, the comments have been added for clarity.

| <u>Part Program</u> | <u>Comments</u> |
|--|--|
| • | |
| • | |
| • | |
| STRT AT/0, 5, 6 | Initial tool position off work |
| FEDRAT/. 75 | Feedrate of tool |
| PS IS, ELLPAR/8, 3, 6, . 25, 0, 0, 0, 1, 0, 0, 0, . 33333 | Description of part surface |
| TLRAD/. 6875 | Tool Radius |
| TOL/. 05 | Cutting tolerance |
| GO FWD/SPIRAL | Start tool from point 0, 5, 6 and go to nearest point on base-cut around part made previously by APT II statements. Make spiral cut se- quence upward around part to top, and return to point 0, 5, 6 |
| • | |
| • | |
| • | |
| • | |

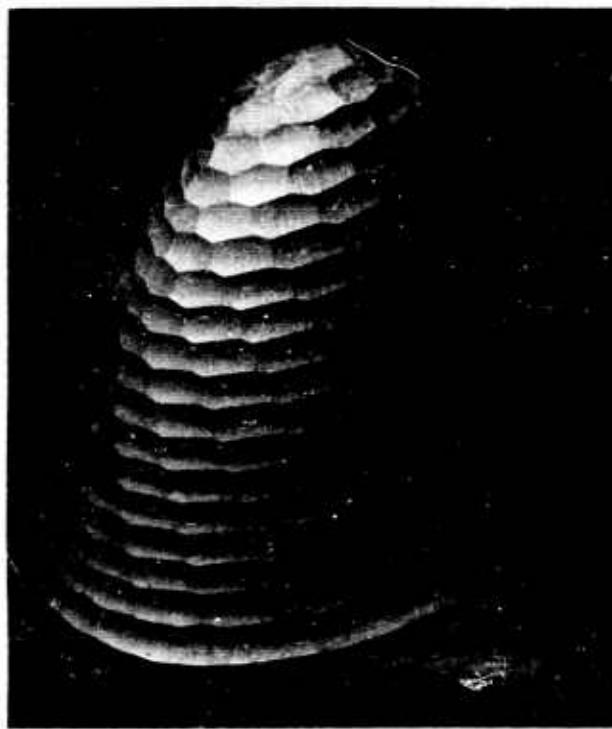


Fig. II-7 Elliptical Paraboloid Cut with APT III

It is evident by comparison of this last part and its program with those previously presented that the APT III region programming greatly reduces the required labor on the part of the part programmer, and greatly simplifies the part program. Note in Fig. II-7 that the APT III program automatically generated a spiral cut pattern, starting at the base and working upwards, choosing the pitch of the spiral so that the surface tolerance condition was satisfied between adjacent cut paths, as well as along the path. As an alternate to the spiral finishing pattern, a zig-zag pattern can also be specified. It will also be noted that the individual cut vectors are longer where the part curvature is least and that the cut vector pattern is slewed as a result of the shortening path length around the higher portions of the spiral. Calculation of this same part by the APT II system would require a separate instruction for each circuit around the part, plus an indexing instruction between each such path.

E. OTHER COMPUTER PROGRAMMING ACTIVITIES

In addition to the APT II and APT III prototype systems on Whirlwind

and the technical liaison with the industrial APT II project (to be described in Chapt. III) the project has engaged in a number of other programming activities related to APT system development. Two of these, the Group Control and Perspective Scope Plot programs, were written as the project's contribution to the industrial APT effort. Two other programming efforts, carried out on the IBM 704 computer but not directly related to the industrial APT effort, were thesis studies which treat problems of interest in computer applications such as APT; a digital computer analysis method for simple English sentences, and a method for automatic selection of initial values for iterative procedures. Finally, considerable experimentation was done with the new technique of "list" programming, which is expected to form a foundation for future developments in APT systems, and in computer-aided design. These five activities are described briefly in the following paragraphs.

1. 704 Group Control Program

The Group Control program is a "facility" type of program which has nothing to do with the simulated APT computer per se, but which adds greatly to the flexibility of the general purpose computer when used for APT programs. Actually, the program is quite general in nature and could be used for any large 704 program; however, the coding language used at present is keyed to the APT programs.

Whenever a program exceeds the capacity of the high-speed memory (usually magnetic cores) in the computer, part of the program must be stored in slower-speed memory devices, such as magnetic drums or tapes. Since program addresses in general refer only to locations in the high-speed memory, program segments cannot be operated directly from the slow-speed memory and must be transferred to high-speed memory before use. Under these circumstances, the computer programmer must arrange for all necessary movements of program segments (or groups) into and out of the high-speed memory and this requires a considerable amount of programming effort, particularly in programs containing a large number of conditional transfers (jumps) in the instruction sequence. The Group Control program, which always occupies part of the high-speed memory, acts to arrange for all needed interchanges of program memory segments without requiring specific instructions from the programmer.

When at any point in a program it is required to transfer to another point in the program which is not currently in the high-speed memory, the Group Control program automatically brings the required program segment (or group) into the high-speed memory, saving any partial results needed in the transfer, and saving or storing the original high-speed memory contents as required. In essence, the programmer can write his program as if the computer had an infinitely large high-speed memory and need not worry about the details of program control.

The 704 Group Control program was completed and program decks were distributed to the industrial APT project in the fall of 1959. The program is completely described in APT Volume VII which is scheduled for distribution in April, 1960.

2. The Perspective Scope Plot Program

The second part of the industrial APT II program contributed by the project is the program for displaying the output of the APT II calculations on the 704 oscilloscope. By means of this program, perspective views of parts may be shown on the scope in terms of the cut vectors which have been calculated over their surfaces. Typical scope plots showing three-dimensional perspective views of the elliptical paraboloid discussed earlier, and of a saddle surface are shown in Fig. II-8. These particular examples are from a Whirlwind program.



Fig. II-8 Perspective Scope Plots of Three-Dimensional Surfaces

The Perspective Scope Plot program is designed so that the human operator has a wide degree of flexibility in controlling what he sees on the scope. By manipulation of console switches, the operator may rotate the three-dimensional view of the part being shown about any axis and thus observe it from various aspects as an aid in deciding if the computer has calculated the correct part. Provisions are also provided for offsets and scale changes so as to expand a particular portion of a presentation. There is also considerable freedom in the control of what is displayed and when. Thus each vector may be displayed as it is calculated, or the display can be omitted until after all vectors are calculated. This latter is an important feature because display routines are usually much slower than other digital computer operations, and APT calculation speed is reduced if display is continuous. However, there may be instances where a vector-by-vector display is desirable. Permanent pictorial records of parts are obtained if desired from the scope camera which is operated by the program under direction from the console.

Several versions of the scope plot program were completed and tested during the contract period, both on Whirlwind and the IBM 704. Although a supposedly final APT II version for the 704 was being completed at the end of the contract, and was to be distributed in December, 1959, it was decided that further modifications and additions were required before the program could be distributed to the APT project. The necessary program revisions and preparation of the documentation, to be issued as new chapters for Volumes II and IV of the APT documentation, will be carried over into the new contract as part of the APT liaison work.

3. Selection of Initial Values

This thesis study, published as Technical Memorandum 6873-TM-12, describes a scaling technique for obtaining initial values for iterative procedures which find the zeros of arbitrary functions. The method seems promising in that it is a systematized procedure which can be used wherever analytic methods are not applicable, or where trial-and-error methods are too uncertain. It appears particularly promising in two difficult situations which occur with iterative procedures: (1) where the iterative procedure diverges for all initial values outside a small neighborhood of each zero, and (2) where it is necessary to obtain several or all of the zeros of some function. Both of these situations are overcome using the scanning technique.

The general idea of the method is to select likely starting values for an iterative procedure by locating near-minima of the function which are isolated by peaks or ridges. This is accomplished by evaluating the function in question at a mesh of points distributed over a selected region. Then an orderly comparison procedure, based on various logical tests, is used to make successively unlikely starting values. The final step is the selection from the unmarked points of the most likely points which are isolated from each other by marked points.

4. English Language Input to a Computer

A second thesis study, published as Technical Memorandum 6873-TM-9, treats the problem of how an English language structure can be used to convey ideas to a digital computer. The major problem is to extract the individual thoughts from the sentences to transform the ideas into meta language statements which are meaningful to the computer. In accomplishing this, the goal is to devise a scheme whereby sentences may be written in any order or in any style to the individual's liking and still be decipherable to the computer. Such a scheme would offer broad benefits over present computer input languages which tend to have rigid un-English-like formats and which are actually quite restricted in the ideas which they can convey. Examples of the present part programming language in which APT statements must be made have been presented previously in this chapter. An example of a normal English sentence decipherable by the CONTACT program developed in this study is as follows:

GO RIGHT ALONG THE LINE THROUGH THE POINT $x = 1, y = 2$
AND $x = 2, y = 2$ TO LINE 2.

The CONTACT program has the following restrictions imposed on sentence structure:

1. Only those words which appear in the official vocabulary list may be used.
2. The present tense must be used exclusively.
3. Complex sentences (i. e., sentences with more than one independent clause) are not permitted.
4. Idiomatic expressions may not be used.
5. Symbolic names or quantities defined by the human which do not appear in the vocabulary list must contain at least one number and one letter.

Despite the success achieved with CONTACT, a great deal of further work should be done to reduce these restrictions on input sentence forms. Also, only part of the computer program was completed and tested as part of the thesis research.* It is expected that further research in this area will be conducted under the new contract.

5. List Programming

With the knowledge that the future extensions of the APT systems and the application of computers to aid in the mechanical design process will place extremely heavy demands on computer programming technology, investigation and experimentation has also been done with the new technique of "list" programming.

A list is essentially an ordered set of elements, and each element of a list may itself be a list; also each element of a list refers in some manner to the next element of the list. From these properties the following advantages of using the list concept in computer programming may be deduced.

1. Since each element of a list may be a list also, there is no limit to the extent or depth of modification of any element.
2. Because each element is referred to be the preceding element, additions and deletions of elements to a list are relatively simple procedures.
3. Because of this referencing feature, it is not necessary to reserve large blocks of consecutive storage locations when programming with a list system.

Professor John McCarthy of the M. I. T. Research Laboratory of Electronics has been developing a list programming system for the IBM 704 which is known as LISP (for List Processor) programming system. In the latter part of 1959, the project developed a preliminary version of a system for the manipulation of mechanical design information, using the LISP concept. As was expected, the LISP system was satisfactory for coding the part of the language used for the symbolic manipulation of data. However it proved to be both inflexible and inefficient for coding of numerical calculations. Therefore, modifications of the LISP concept are planned for future project

* Some parts of the CONTACT program rely on the COMIT information manipulation routine being prepared jointly by the Computation Center and the Research Laboratory of Electronics at M. I. T., and which is not yet available.

work in this area. Complete details of the LISP programming experiments, and a resume of the concept are presented in Interim Report 6873-1R-10 and 11.

F. MACHINE TOOL TECHNOLOGY

Despite the advanced state of development of machine tool directors and controls, there are still areas where substantial improvements can be made. In particular, it appears that numerical control is "open-ended," because there is at present no system in use in which any feedback exists from the actual cutting process to the machine director, or to the computer which is providing the machining instructions; thus it is difficult to program the tool so that it is always operating at maximum efficiency. It is also difficult to say that the present division of functions or computational load between the numerical machine control director and the APT computer is the best one. Since the machine tool director may be looked upon as a piece of special purpose peripheral equipment for the computer, the level of information transferred between the computer and director is arbitrary and the directors could be designed to do more or less work than at present, with the computer's job being either smaller or larger in proportion. These questions have been studied in two thesis projects supported under the contract. Thesis work has also been done on improvement of tracer machines by use of adaptive control. These various studies are summarized in the paragraphs below.

1. Automatic Feedrate Control

Although tool feedrates are specified by the APT part programmer, based on his knowledge of metal cutting and information available to him on the machine and the size of the cut, it is obviously impossible to foresee each cut accurately enough to program maximum feedrates. Since too heavy or too fast a cut can severely limit tool life, and can even break tools and cause part damage, it is usual for the programmer to allow a safety factor in scheduling feedrate. However, metal cutting at these reduced rates is costly in terms of production time and expense. Some control of programmed feedrates is at present exercised manually by machine operators, but this requires close attention at each machine and does not necessarily result in maximum output. If an automatic feedrate control were employed in the

director or the tape playback, the programmed feedrate could be adjusted up or down as required for each particular cut so as to provide maximum output. Of course, other factors, such as surface finish, may still require reduced cuts and feedrates at times.

An initial technique which was investigated for measuring tool load was to measure the torque in the machine tool shank. A strain-gage bridge, arranged to be sensitive to tool torque but not to tool bending, was affixed to a variety of tools and cutting tests were made on the M. I. T. numerically controlled milling machine which incorporates a Cincinnati three-axis miller. Before these tests, the miller was modified to permit carrying the strain-gage signals from the tool spindle by means of mercury slip rings. Although these tests indicated that it was indeed possible to measure tool torque and to derive a signal proportional to it, subsequent information indicated that tool torque is not particularly significant as a measure of tool wear. Consequently, work has recently been directed at utilization of temperature measurements at the cutter-work interface. This temperature can be measured by the thermocouple emf generated between the tool and the work.

Results of the initial torque measurement studies were recorded in Interim Engineering Report 6873-IR-8 and 9 for the period ending February 28, 1959. In the intervening period, methods for practical measurement of the cutter temperature by the thermoelectric effect had been developed. This measurement is complicated by the necessity for insulating either the tool, the workpiece, or both. Although tests have been made at M. I. T. with an insulated workpiece, for simplicity in experiments, an insulated tool would be preferred in actual use since it is difficult to keep chip accumulation from shorting an insulated workpiece to the machine tool table. These studies also indicate that it will be desirable to utilize a two-input control system, in which one input maintains a constant peak cutting temperature at the interface between the tool and workpiece, and the other provides a limit on bending of the cutter. This second bending input is easily obtained by a modification of the strain-gage measuring system previously utilized for measuring cutter torque. The purpose of the bending input is to protect the tool from gross bending deflection such as would occur if an attempt were made to cut with a non-rotating tool.

Studies have also been made of the M. I. T. numerically controlled machine in order to ascertain how the temperature and bending signals can be used to provide the desired machine control. As of this writing, all of these studies are complete but complete closed-loop tests have not been made. Status of this work is reported in detail in Interim Report 6873-IR-10 and 11, and the work itself, including modifications to the machine tool director and the conduct of experiments, will carry over into the new contractual period.

2. Curvilinear Interpolation

The second study in machine technology concerns the possibility of placing more of the computational load in the numerical director. Historically, the present level of input information to some directors was chosen at a relatively early stage in digital technology and on the basis of initial concepts that a director would be part of each tool. Thus the directors were designed to do relatively simple tasks. With changes in the usage of directors, and advances in digital technology, it is now appropriate to consider assigning more of the computational load to the director, where with special-purpose configurations the calculations can perhaps be performed more efficiently than in general purpose computers, such as the IBM 704.

An example of a new technique which makes such an increase in the director capabilities possible is incremental computation. The great majority of numerically controlled tool systems function incrementally, that is the input signals direct the tool to move a specified increment (Δx_1 , Δy_1 , and Δz_1 ,) rather than directing the tool to move to a specified point (x_1 , y_1 , z_1). Thus the use of incremental computation fits in naturally with numerical control. Digital differential analyzers (DDA's), which are one class of incremental computers, permit great savings in computer equipment and improvement in computational speed for problems involving essentially smooth computation, typical of such physical operations as moving a tool over a workpiece. The digital differential analyzer (DDA) combines the accuracy of a digital device with the simplicity of programming an analog differential analyzer.

One way in which increased computational capacity in the director could help is to permit use of curvilinear interpolation, the process whereby segments of specified curves, rather than straight lines, are used to approxi-

mate the desired part. This has two advantages over linear interpolation. First, the parts will be smooth, so that the labor involved in hand-finishing a completed part is either reduced or eliminated. Second, the length of each cut will be longer so that fewer input data points to the director are necessary. The most common type of curvilinear interpolation used is parabolic interpolation, where the tool moves along segments of parabolas, although other curves may be used. The disadvantage of parabolic interpolation or any other curvilinear interpolation is that the computations, although fewer than for linear interpolation, become much more complex. Thus, a system which could provide curvilinear interpolation, while at the same time greatly reducing the difficulties in computing cuts would be quite advantageous.

In the study which was made, a curvilinear interpolator utilizing DDA techniques was designed as an addition to existing directors. Although this interpolator was designed to be compatible with the M. I. T. numerically controlled machine tool, the design can be easily modified for use with any other director. Since there was no requirement for actual construction, the curvilinear interpolator was simulated using the TX-0 transistor digital computer at M. I. T. and several test parts were calculated. Although only the two-dimensional case was simulated, extension to three dimensions is straightforward. It is concluded that the technique is feasible, but that parallel rather than serial logic would be required in the DDA in order to perform the necessary interpolations in real time. A full description of this study, including results to date and problems yet to be solved in constructing an actual curvilinear interpolator, is given in Technical Memorandum 6873-TM-10.

3. Adaptive Control for Tracer Machines

In another thesis research not directly connected with numerical control, a study was made of adaptive control as applied to tracer-controlled milling machines. The study, described in Technical Memorandum 6873-TM-11, shows that additional measuring probes contacting the template ahead of the cutter location can be used to improve the control system response. However, no tests of such a system were made on a machine tool nor was any attempt made to design such a system of probes. Response tests of the system were made by simulating the mathematical model on an analog computer.

G. COMPUTER AIDS TO DESIGN

During the last twelve months of the contract, one task has called for initial studies of possible extension of numerical control and automatic processing techniques to include more of the total manufacturing process than at present. This section presents a brief summary of the findings to date, which are reported more fully in Iterim Reports Nos. 8, 9, 10, and 11. Continued study of this area forms a major part of Contract AF-33(600)-40604 which continues numerical control work at M. I. T.

With the combined use of numerically controlled tools and high-speed digital computers, as represented by the APT system, it is now possible to go directly and automatically from drawing information, as interpreted by a human part programmer, to part fabrication. Thus a substantial part of the overall manufacturing process has been made automatic. However, as yet little has been done to reduce the considerable amount of manual data processing involved in design and drafting prior to the construction of the usual engineering drawing. Examination of the total manufacturing process, which starts with the part specification and ends with the finished part, indicates that it is technically feasible to continue the application of automatic data processing so as to include much, if not all of the manual design, drafting and part programming processes which at present precede the APT system. Thus a new goal for numerically controlled manufacturing is to go directly from part specifications to completed parts with the aid of automatic data processing techniques.

1. Analysis of Manufacturing by Numerical-Control Methods

One characteristic of current numerical-control manufacturing methods is that the information involved in the process is derived from an engineering drawing of the part to be manufactured. Thus, at present, the numerical-control process starts with an engineering drawing, undergoes a programming stage and then through a general-purpose computer stage in order to translate the information on the engineering drawing to digital form, proceeds to a digital interpolator (director) to prepare the digital data for the specific machine-tool involved, and finally ends at the fabrication stage where the part is machined by servo-controlled machine tools. This sequence is shown in Fig. II-9.

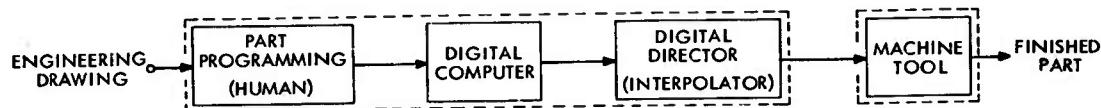


Fig. II-9 The Numerical-Control Process

In the over-all process of obtaining a mechanical part to perform a function or set of functions, an area which has not been subjected to critical investigation in the light of modern technology is that which concerns the design process itself; that is, the part of the over-all process which precedes the engineering drawing. As a preliminary to a discussion of possible ways in which digital computers may aid the design process, consider Fig. II-10. This figure is similar to Fig. II-9, except that the design steps which precede the working drawing are also included.

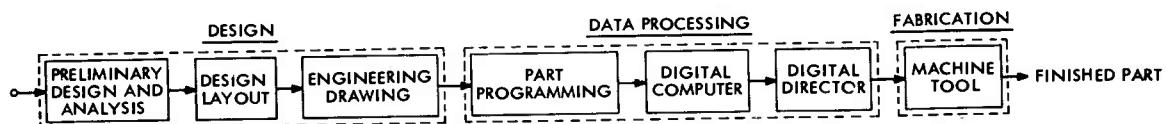


Fig. II-10 The Over-all Manufacturing Process Using Numerically-Controlled Machine Tools

It will be noted that part of the design stage concerns the generation of a configuration which may reasonably be expected to fulfill the requirements, and a mathematical analysis of the configuration. These operations may be termed preliminary design and analysis, and the design engineer plays a dominant role in them. The design layout finalizes the preliminary design and yields data for preparation of the engineering drawing. In the design-layout stage, the design draftsman and engineer work together, while designs that are released for drawings are usually under control of the drafting group.

Another way of looking at the over-all manufacturing process is to regard it as being made up of three parts: information generation, information processing, and information utilization. A point to be noted in Fig. II-10 is that these three parts do not constitute an uninterrupted continuous process. Rather, several information-storage points exist.

Information concerning the mechanical part which will meet requirements is generated in the design stage, and in accordance with present procedures, this information is stored in graphical form as engineering drawings. The graphically portrayed information is later transformed into coded-language form and stored (in the APT system of automatic programming) as English-like typewritten instructions. These instructions are then processed in a digital computer and stored as numbers on tape. In some numerical-control systems, a fourth information-storage point exists just prior to the machine tool itself, where data are stored in magnetic form on magnetic tape. These four storage points are shown in Fig. II-11.

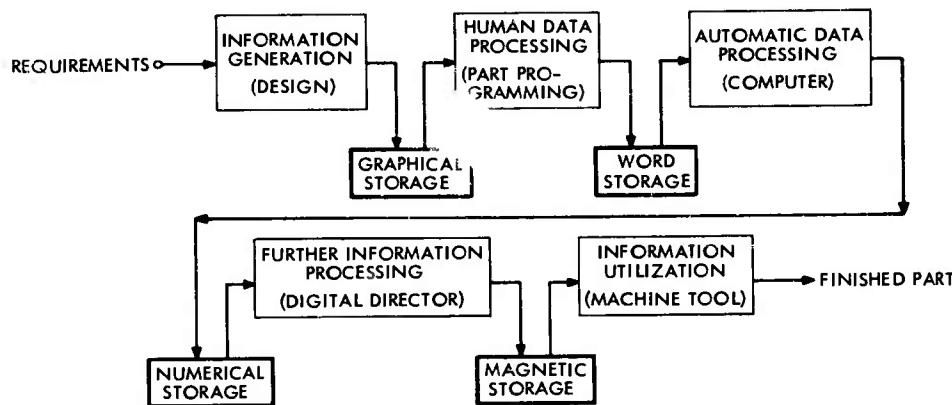


Fig. II-11 Information-Storage Points in the Manufacturing Process

2. Possibilities for Computers in the Design Process

To date, the use of large-scale digital computers for design has been confined to situations where design procedures can be described analytically. When variations of a specific class of machine or device are then desired, the new design is carried out automatically by varying design parameters. Examples are the present use of computers in industry to design motors, transformers, turbines, stressed structures, etc. In these applications, all the steps in the design process are known and can be expressed in a form which can be executed by a computer. The computer is then useful for generating a new design which is a "scaled" version of the original machine of its class.

As opposed to the above use of computers in design, we may postulate an original- or creative-design machine. In this type of machine it is

unreasonable to expect that the computer would be able to carry out the design completely unaided by the designer, since originally the design would be unspecified. Hence, it appears that the role of the computer in an original-design process would be that of a tool for the engineer to assist him in arriving at an acceptable design. Thus it will be necessary to develop methods which will enable the designer and computer to work together in order to achieve a satisfactory design.

One of the prime difficulties in "teaching" either engineers or computers to perform or assist in mechanical design is to reduce a process which is sometimes considered an inborn art to a set of rules. During the past year, a survey of the design process has been underway by the project with the active assistance of the Mechanical Engineering Department at M.I.T. Happily, this has coincided with a resurgence of interest on the part of engineering educators in analyzing their methods of teaching design, thus there are many willing hands for this work. First results of the survey and analysis, covered in Iterim Reports 8 through 11, illustrate the approaches being taken, but also indicate the magnitude of the job ahead. It is expected that the main work of the next contractual year will be further study of the design process, and of new computational techniques, to facilitate design calculations, after which definite avenues of approach to a system of computer aided design should be evident.

Another aspect of the design process which needs investigating is the graphic drawing. One might ask the question: "Why should design information be stored at all in graphical form, since later it is translated and stored in other forms ?" In other words, is it possible to bypass the drafting room entirely ? Because of the great many man hours consumed in storing information graphically, a major accomplishment would result from the elimination of most of the drafting room. At present it is unclear whether or not the drafting room could or should be completely bypassed. It may be that some visual representation of the object being designed should always be preserved. However, there exists a good possibility that satisfactory visual representations could be preserved by means of sketches photographed from the output oscilloscopes of computers, with the more precise information preserved on cards or tapes from the machines.

Should this procedure prove undesirable or impractical, alternatives exist. It may be feasible, for example to eliminate one or more of the

other information-storage stages depicted in Fig. II-11, thereby simplifying the process. Alternatively, if it turns out that preservation of information in graphical form is necessary, it may be possible to automate the drafting process. Answers to these questions will hopefully come from work now going on.

In future investigations, the goals are to use computers as aids for achieving

- a. better designs with a higher confidence factor that they will meet specifications
- b. a reduction in time consumed in the over-all manufacturing process
- c. flexibility to accommodate design changes easily
- d. reduction in costs of the over-all manufacturing process

It is recognized that realization of these goals will require substantial advances, both in computer technology and in the understanding of the design process. Those familiar with the present operation of APT on the IBM 704 may perhaps feel that the computing requirements would be prohibitively expensive. However, computers one hundred times faster than the IBM 704 are now being installed, and another factor of ten or perhaps one hundred is on the horizon. Continued rapid progress in computer technology and in the techniques for using computers makes it evident that these goals are not too far away.

CHAPTER III

THE AIA SPONSORED JOINT PROGRAMMING EFFORT

A. INITIATION OF THE JOINT EFFORT

In January, 1957, at about the time when the M. I. T. project had completed its general formulation of the APT system concept and had a limited prototype system operating on the Whirlwind computer, members of the project attended a meeting of the Numerical Control Panel (NCP)* of the Aircraft Manufacturing Equipment committee for the Aerospace Industries Association. The NCP had been formed to study how numerical control could affect the aircraft industry and to study the possibility of standards and specifications in the field of numerical control. One of the many projects actively under study by the panel was the problem of part programming, and the M. I. T. observers at the meeting made a brief progress report on the M. I. T. project for the information of the panel members. The new analysis and comprehensive approach of the APT system concept aroused substantial interest on the part of the panel members, and the data processing study group of the NCP was asked to review its work in light of the information presented by M. I. T.

A meeting of the NCP data processing study group was held in Los Angeles in April, 1957. At that meeting each aircraft company's approach to computer programming for numerical control was examined and compared along with the M. I. T. programming concept. In this review the M. I. T. approach was, in the consensus of the study group members present, the most promising because of its capability for future expansion to incorporate more sophisticated time-saving programming procedures. Many points of similarity and/or compatibility were discovered among all the approaches, and it was felt that much of the work and programming in the postprocessing and output area already accomplished by individual companies would be applicable, with modification, to the new approach of broader scope. Thus, a substantial start was made at defining a new common automatic programming approach combining the best features of all existing methods. A

* Then called the Subcommittee for Numerical Control

tentative list was established indicating which plans would be the most suitable to accomplish each part of the overall common group effort. At the time of the April study group meeting, it seemed that with early and effective work by each assignee it should be possible to obtain usable results by October, 1957.

The study group further decided to recommend to the NCP that M. I. T. be considered to be in the best position to coordinate all the plans in this joint programming effort. Such coordination would include any necessary instruction in the system concept, dissemination of information on progress and results, assistance in technical problems to ensure common philosophies and program compatibility, surveillance over individual progress, and coordination of the final results for distribution. These views were enumerated by the study group to underscore the benefits to be gained by such an undertaking, such as reduced individual cost and data processing compatibility. The following formal recommendations were drawn up by the study group at its April meeting and presented to the NCP meeting which followed a few days later.

1. Sponsorship of Program Work

Each aircraft plant assigned Air Force numerically-controlled machine tools, and planning to perform data processing on the IBM 704 computer should take at least one of the parts of the system and solve that as part of the contribution to the joint effort. In return, all companies would receive the results of the total joint effort.

2. Coordination of Effort

In order to give the assigned programmers from each participating company sufficient detailed information regarding his share of the overall effort, to establish common links between input and output of different programming portions, and to familiarize programmers with the new common approach, programmers from all participating companies were to spend one week at M. I. T. The time of the meeting was tentatively set for the week of May 20, 1957.

These recommendations of the data processing group were endorsed by the NCP at its April, 1957 meeting. It was strongly emphasized that the recommended joint effort on the part of all companies concerned was essential in order to provide the necessary computer programming for use with numerically controlled machines then being delivered to the companies. Also, it was felt that the proposed division of responsibility and workload among a number of companies on a coordinated basis

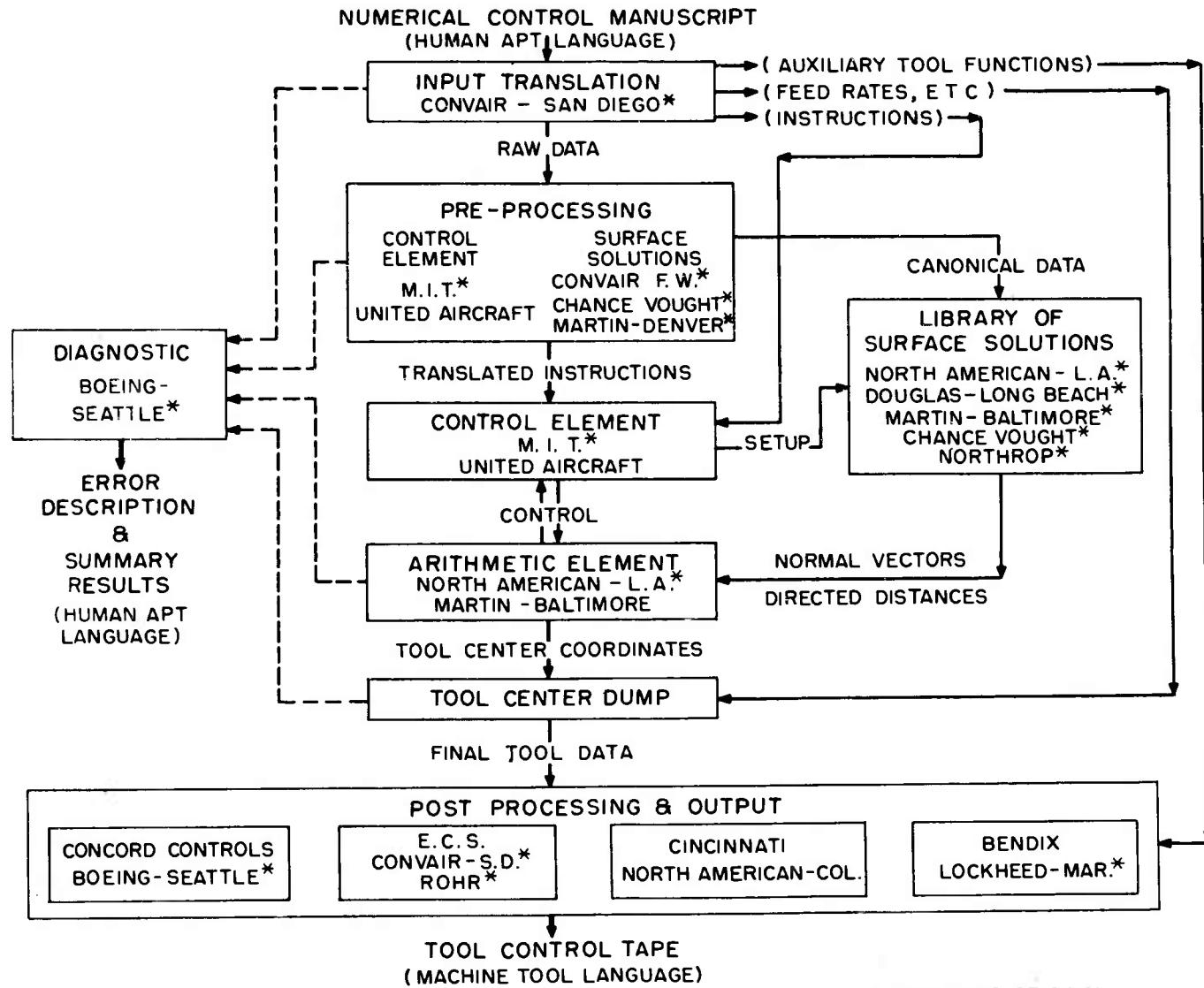
would make it possible for all companies to have computer programs at a reduced individual cost in a much shorter space of time than would be possible with individual effort. The output of the joint effort was to be, first, a deck of cards usable on any IBM 704 series general purpose computer, and, second, all the necessary information required to program a part. A smaller group of companies was also formed to consider the programming of an APT system for the IBM 650 computer. When, after a few meetings, the group was unable to agree on which version of the 650 computer would be considered standard, the group dissolved, leaving the IBM 704 computer as the only computer on which the APT system would be developed initially. In order to achieve uniformity between the various problem group activities, M. I. T. accepted overall responsibility for technical coordination.

B. REVIEW OF THE JOINT EFFORT

The programmer's meeting at M. I. T. in May, 1957 was attended by 21 persons, most of whom were experienced computer programmers, from 14 different aircraft companies and plants. During the one-week meeting the purpose and functioning of the automatic programming system which was to result from the joint effort were discussed and a design was formulated, based on the M. I. T. Whirlwind prototype APT II system, for what later became known as the 2D APT II system. The abbreviation 2D was included to show that the initial system was to have a part programming language for producing two-dimensional parts, and the abbreviation APT II indicated that the system was to be programmed in terms of three-dimensional space curves. At the May M. I. T. meeting, programming conventions were established so that the large programming task represented by the 2D APT II system could be performed by the individual programmers working at their own plants, with coordination carried out primarily by mail and telephone.

Sponsorship of the various portions of the 2D APT II system as of February, 1959 is shown in Fig. III-1. Those companies marked with an asterisk were the original workers on a particular portion, while unmarked companies undertook work at a later time. As noted at the bottom of the figure, a number of other companies held program decks, but had no basic programming assignment as of February, 1959. This

PHASE I PROJECT COORDINATION - M. I. T.*
 PHASE II PROJECT COORDINATION - NORTH AMERICAN AVIATION



* INDICATES ORIGINAL ASSIGNMENTS

OTHER CARD DECK HOLDERS

| | |
|---------------------------|------------------------------|
| MC DONNELL - ST. LOUIS | GOODYEAR - AKRON |
| IBM - WHITE PLAINS* | MARQUARDT - VAN NUYS |
| BELL - BUFFALO | REPUBLIC - LONG ISLAND |
| LOCKHEED - BURBANK | GRUMMAN - LONG ISLAND |
| UNION CARBIDE - OAK RIDGE | NORTH AMERICAN - ROCKET DYNE |

Fig. III-1 APT II Programming Assignments as of February, 1959

situation is now much changed, and information on current assignments can be obtained from the AIA.

Although it had initially appeared that usable results could be obtained by October, 1957, there was considerable schedule slippage right from the start. Because of previous work commitments, innumerable difficulties were encountered in starting up individual programming tasks at the various participating companies. As a result, the October, 1957 deadline for initial programs was postponed to January, 1958, and at the same time the original scope of the program was reduced to include only those parts which could be assembled into a minimum-size working system to be called the Phase I 2D APT II system. It was also decided that the M. I. T. involvement in the joint effort was to cease as an active participant on the completion of this initial working system. Even the January, 1958 deadline could not be met, since individual decks from the participating companies were not all received until the end of January and early February. Furthermore, unavoidable communication problems between people working on the system prevented all the pieces from matching up, and a certain amount of debugging had to be done to provide compatibility between the various pieces received. While problems in the programs were primarily clerical and not serious in magnitude, they did involve considerable expenditure of effort on the part of M.I.T. personnel during February, March, and a large part of April, before an operating system was achieved. Also, a constant stream of corrections came in from the participating companies during the debugging period, and were incorporated into the program deck. In April, 1958, 17 copies of the field trial version of the Phase I system were mailed to the companies for further testing and debugging evaluation. The field trial package included some 8,000 computer cards and about 200 pages of preliminary documentation prepared by the various individuals who wrote the programs. Operating and part programming instructions also were included, along with a few sample test parts for use in testing out the system.

The field trial period continued until the fall of 1958, and with this stretch-out, various facilities which had been originally scheduled for later versions of the APT systems were included in the original version. After these additions, it was found that the resulting programs could perform almost all basic three-dimensional work automatically, and the 2D prefix

was dropped so that the official name became APT II Phase I. By this time several aircraft companies were actively participating in the continued development of the APT program. In the summer of 1958, the AIA APT Project Coordinating Group took over active coordination of the entire effort from M. I. T. so that M. I. T. could devote its efforts to the writing of the 6-volume APT Manual to accompany the "finished" Phase I system. Since that time the coordination and running of the APT effort have been solely the function of the AIA, and M. I. T. has continued only as a deck holder and consultant to the effort.

The various volumes of the APT Manual have been completed and distributed in 1959 (see Chapter IV), except for Volume III "Mathematics of the APT System" which was to present the general derivations of the data processing techniques employed. Volume III is now reserved for description of a new APT analysis, and will appear in 1960 as explained in Section D. Also, a new Volume VII added to the manual to describe the Group Control program will appear in January 1960. The group control writeup had been originally scheduled as a chapter of Volume IV.

C. THE MANY VERSIONS OF PHASE I

A continuing problem of APT system development has been that of keeping the program decks in all of the various companies up to date. Even today the system cannot be considered a completely functioning system. Corrections and modifications are continually being made by everyone using the system, either to remove some newly-discovered fault or to incorporate completed results of a programming assignment. As a result, throughout this developmental period numerous change decks for modifying the basic program have been circulated to the participants in an effort to make the latest results available to all. Categorization of these changes as "information only" changes and "official" changes has somewhat alleviated the problems which arise from changes to the basic program, followed by changes to the changes. Periodically, however, it has been necessary to have a general housecleaning by replacing the entire system throughout the industry by a re-issued master program deck. So far, all of these re-issued decks, intended primarily to give a more workable version of the previous deck, have been called "Phase I" decks of various types, leading to no little confusion in terminology.

The first Phase I deck was that assembled and issued by M. I. T. for the field trial period. This deck, although suitable for debugging purposes, was an assemble of only those basic portions of the system which were needed to make a minimum functioning system and had no definition preprocessing features and a number of peculiar part programming conventions. For this reason, the Field Trial Deck was not considered suitable for general production use.

When M. I. T. turned over coordination to the AIA group and took up the documentation task, it was decided that the M. I. T. documentation would describe not the Field Trial System then in existence, but the revised Phase I system to be completed by the industrial group. It was hoped that the program changes would be completed when the documentation was issued so that Phase I would be a reality. However, the situation has not proved to be this simple. As the work of programming and documentation progressed, a number of the new changes were issued as additions to the Field Trial Deck, and several items originally scheduled for Phase II were incorporated into the documentation and program to give a better Phase I. Many of these changes were covered in a "Post Coordinator Report" issued by M. I. T. to describe the program changes which would be required to match the documentation.

The decision to describe the APT system features at an AIA-AMC-MIT Press Conference at M. I. T. in February, 1959 gave further impetus to these proceedings. In order to be able to demonstrate the system publicly, it was necessary for M. I. T. to re-enter the programming and debugging work and assemble a system containing all but a few of the Phase I features, most of which were not yet working and available throughout the industry. The result was that the Press Conference system at M. I. T. was the most complete and operative system available in February, 1959.

An APT programmer's meeting was held at M. I. T. the week of April 27 to May 1, 1959. In addition to the discussion and scheduling of numerous Phase I and Phase II changes, a new "deck" was issued by M. I. T. (courtesy of IBM) by recording the M. I. T. Press Conference system on IBM 704 magnetic tapes which each programmer had brought with him. It developed later, that for one subtle reason or another, many portions of these recordings were unusable, so most programmers continued with modified Field Trial Decks.

Following the programmer's meeting, M. I. T. completed the printing and distribution of all except Volume III of the APT documentation and continued work on its two assignments, the Group Control Program, and the Perspective Plot Program. Meanwhile, the industrial group continued with the task of refining and expanding of the APT II system. Almost all of the original assignments made in May, 1957 had now been completed separately and required only integration into the system. Many new companies had also joined the effort, and were becoming sufficiently familiar with the system to make valuable contributions. In this intervening period so many facets of the newly completed work had crystallized, that a new, and this time final, "Official Phase I" deck with well over 25,000 cards was issued by APT Project Coordinator, Mr. Len Austin of McDonnell Aircraft, St. Louis, following several weeks of intensive work with the assistance of programmers from several companies. All further changes are being made to the Official Phase I Deck, and it is planned that the next major re-issue will be Phase II in mid-1960.

With so many changes being made on a continuous basis, one difficulty has been that the documentation has never exactly fitted the programs or vice versa. In some cases the programs described in the documentation have been subsequently changed, and in other cases the documentation describes a program which is still being worked on and is not yet a reality. This situation is considered to be typical of any system in a state of fluid development and should improve as the rate of change in the APT systems tapers off. Of course, the APT manuals will require continual revision as changes are made, but this should approach an orderly procedure.

D. NEW ARELEM

In mid-1959, it became apparent that there were serious deficiencies in the Arithmetic Element Program ARELEM of the Phase I system which made it difficult to use for certain parts. Also, even when the program did work it computed out-of-tolerance cuts unless very small maximum cuts (max-DP) were specified by the programmer. The APT Project Coordinator had several people in industry working on fixes and improvements, but at an August 23-27, 1959 meeting in Denver also asked M. I. T. in its role as consultant to investigate the problem. In the period from September to November, 1959, M. I. T. has established the basic features of a completely new analysis for ARELEM which should solve all the current problems,

and which can also have far reaching effects on the remainder of the APT system. Although part of the new analysis will be usable immediately as a patch for the Phase I system, and a second more extensive portion can be included in a Phase II system, eventual realization of all the potential of the new analysis will require rather complete revamping of the control, preprocessing, and input translation parts of the APT system. A preliminary description of the features of the new ARELEM is given in Interim Reports 10 and 11.

Coding of the new ARELEM is again being handled on a joint basis. M. I. T. has prepared a detailed flow chart for the analysis, and a number of companies will perform the coding. A week-long meeting of the selected programmers was held at M. I. T. December 7-11 at which assignments were made and programming conventions established. It is tentatively planned to meet again at M. I. T. in February for program assembly and initial debugging. The extent of further work by M. I. T. in support of the AIA-APT effort under one task of the new M. I. T. Contract AF33(600)-40604 is now being discussed with the Air Materiel Command and with the AIA.

When the possibility of a new ARELEM analysis became known, it became rather pointless to continue the original plan to describe the old ARELEM in Volume III of the APT Manual, and it was decided to use this volume to describe the new analysis. Since the analysis will be fluid until after the debugging period, Volume III will probably not appear until mid-summer 1960 at the earliest.

CHAPTER IV

SUMMARY OF PROJECT REPORTS AND PUBLICATIONS

During the period, June 1956 to November 1959, documentation of project activities was performed in a number of ways. Section A briefly describes each type of project documentation and its purpose. Section B contains abstracts of all formal documentation issued by the project, and Section C lists talks and presentations by the project staff.

Approximately 200 copies of each document, except where noted, have been sent to the initial distribution list. Many additional copies of reports and memoranda have been sent in response to specific requests as approved by the Project Monitor, LMBMM. Requests from foreign countries have been very high throughout the life of the contract.

A DESCRIPTION OF DOCUMENTATION

1. Project Interim Engineering Reports

The main subjects of importance in the interim engineering reports are the design and development of the prototype APT II system for the Whirlwind computer, the design and development of the APT III system for the Whirlwind computer, and technical descriptions of the project participation in the AIA APT effort which produced the industrial APT II system for the IBM 704 computer. Summaries are also provided of the supporting activities of the project on language design, oscilloscope programs, studies of adaptive control, digital differential analyzers, and feedrate setting.

These reports were first issued on a quarterly basis, but for the past year, changed to a four months basis. While the numbering sequence of these reports has been maintained in accordance with the reporting periods, slippage in the scheduling of the report writing caused all but one of the interim reports to be combined in pairs as single documents. Thus, the eleven interim reports were actually published as six documents.

2. Project Technical Memoranda

Project TM's (technical memoranda) were originally intended as internal documents to record particular developments which were to be considered complete in themselves. As the project progressed, the material in the technical memoranda proved to be of interest to personnel outside the laboratory, and five of the technical memorandum series were published in finished form and distributed to the mailing list. Subject matter of the TM's includes, for example, surface solutions for the APT system's subroutine library, reprints of talks, student thesis proposals for work of interest to the project and the theses themselves. A notation in the abstracts of Section B indicates which of the technical memorandum series has been distributed outside the laboratory.

3. Special APT Documentation

As part of the project's work as technical coordinator of the APT effort in industry, an initial set of working manuals was produced in early 1959 for use in the industrial APT system. These were originally to consist of 6 volumes. However, as explained below, one of the original six has not yet been published, and a seventh has been added. Volume I is a general description of the industrial APT system, and Volume II is the part programmer's manual for the system user. These volumes have both been distributed.

Volumes III, IV, V, and VI, together were to comprise the computer programmer's manual for maintenance of the system. Of these, only volumes IV, V, and VI have been distributed. Volume III was not issued because of impending changes in the APT analysis, and will now appear in 1960. A new Volume VII has recently been added to the Programmer's Manual, and is being distributed.

The APT Manuals are working documents and will be continually updated and added to in the future by the Aerospace Industries Association through material generated by members of the industrial APT Project.

4. Coordinator Reports and Other Documentation

The APT coordinator reports, of which there were 19 in number, were written and distributed to the working members of the industrial APT project and members of the Numerical Control Panel during the period when M. I. T was active APT Project coordinator. These were working documents intended mainly to take care of details in the day-

to-day activities in the progress of the project. They served the purpose of disseminating information vital to the coordination of the Industrial APT project, and of guiding the efforts of the participating companies. The reports contained, for example: computer coding conventions; questions, answers and detailed discussions on technical matters; changes of assignments; reports on progress on a relatively short-term basis; corrections to the field-trial deck; and information to participants of activities being carried on throughout the effort.

5. Technical Progress Letters

Since the inception of the contract in February 1951, 117 informal monthly progress letters have been prepared and transmitted to the Project Monitor, 42 in the current reporting period. These letters were intended to keep the Project Monitor informed of the technical progress of the work and of the financial status of the contract, and no other distribution was made of these progress letters.

6. Miscellaneous Information Distributed

In addition to the reports described above, the project prepared other material to assist in dissemination of information on numerical control and the APT system.

A special 10-day course on Programming for Numerically Controlled Machine Tools was given by M. I. T. for 57 representatives of companies interested in Numerical Control. While this course was not sponsored under this contract, project members and ex-project members in industry participated as instructors and prepared material for the course; a Course Outline and Workbook, and a group of Selected References. Members of the course aided in producing an Outline of Subject Matter for Industrial Training Programs in Numerical Control of Machine Tools.

A bibliography on numerical control of machine tools listing M. I. T. reports and papers, papers based on M. I. T. work, and important contributions from other sources was sent to the distribution list in February, 1957. Approximately 300 brochures containing a general interest type of information concerning the APT effort were distributed in February 1959 at the AIA-AMC-MIT press conference at M. I. T. Also, a one-half hour television presentation of the APT system was given by D. T. Ross and J. F. Reintjes on the Science Reporter program of Channel 2, Boston on

March 4, 1959. A 16-mm sound film of this television show is available for loan on request to the Electronic Systems Laboratory Library. These items are in addition to those of the 1951-1956 period listed in Appendix A.

B. ABSTRACTS OF PROJECT TECHNICAL DOCUMENTATION

1. Interim Engineering Report 6873 IR-1 and 2, for the period June 26, 1956 to December 31, 1956 by Douglas T. Ross and Harry E. Peple, Jr., 55 pp.

This report is mainly a statement of the APT system philosophy and a discussion of the reasons for setting up the APT system in the form which it originally took. The basic techniques of APT system technology such as the simulated computer, the surface terminology, surface-normal and directed-distance programs, and the basic elementary calculation are covered. Examples are given of the computer plot program and plans for programming by surfaces instead of by curves.

2. Interim Engineering Report 6873-IR-3, for the period January 1, 1957 through March 31, 1957 by Project Staff, 106 pp.

This report describes mathematical analyses for two systems of automatic programming of three-dimensional parts in terms of curves and in terms of entire regions. A new design for the APT II systems is presented, as is the first formal presentation of the region programming. Plans are given for the APT III expansion and test.

3. Interim Engineering Report 6873-IR-4 and 5, for the period April 1 to December 31, 1957, by Samuel M. Matsa, 123 pp.

This report is primarily a technical report on the APT III surface or region programming by Samuel Matsa, but also includes descriptions of other APT work during the reporting period and the initial description of the AIA-APT joint effort.

4. Interim Engineering Report 6873-IR-6 and 7, for the period January 1 to June 30, 1958 by the Project Staff, 149 pp.

In this report the progress of the Industrial APT II system is described. A comprehensive analysis of the current computer oscilloscope program is made, and the current status of the laboratory prototype APT III system is discussed, together with pictures of the parts cut to date.

5. Interim Engineering Report 6873-IR-8 and 9, for the period July 1, 1958 to February 28, 1959 by the Project Staff, 126 pp.

This report contains a discussion of the industrial APT II system activities, including the additions and changes to the programs during the field trial period and complete details on 10 test cases run on the

M. I. T. 704. It also contains progress reports on programming activities (with emphasis on the group control program), automatic feedrate control, adaptive control, special purpose computer designs, and initial results in the study of computer aids to design.

6. Interim Engineering Report 6873-IR-10 and 11, for the period March 1 to November 30, 1959 by the Project Staff, 102 pp.

This is the last interim report for the contract and describes liaison work with the APT Project during the Phase 1 developments of the APT II system following the field trial period, and the features of a re-analysis of the calculation (ARELEM) portion of the APT II system. The final report is given on the Whirlwind APT III studies, and current work on automatic feedrate setting, and automatic selection of initial starting values for iterative procedure is described. Also included are an initial report on the use of computers as an aid to design of parts, to be continued under a new contract, and a report of a trip to machine-tool shows in Paris and Czechoslovakia.

7. Technical Memorandum 6873-TM-1, Summary of Surface Calculations, Jerome Wenker, May 31, 1957, 21 pp. (Limited distribution)

This memorandum describes the methods of solution used to obtain the unit normal and directed distance expressions for surfaces described in terms of vector and algebraic equations. Derivations are given for planes, spheres, cones, cylinders, and general quadrics.

8. Technical Memorandum 6873-TM-2, Preparation for Joint Programming for Numerical Control, Douglas T. Ross, May 1, 1957, 8 pp. (Distributed to AIA/AMEC/Subcommittee for Numerical Control)

This memorandum was written as an agenda and preliminary information release in connection with the May 20-24, 1957 programmer's meeting at M. I. T.

9. Technical Memorandum 6873-TM-3, Papers on Automatic Programming for Numerically Controlled Machine Tools, Douglas T. Ross, January 7, 1958, 35 pp. (Full distribution)

This technical memorandum is a reproduction of two papers written by Mr. Douglas T. Ross, Head of the Computer Applications Group of the Servomechanisms Laboratory at M. I. T. Presentation of the first paper was made at the Third Annual Contour Machining Conference, October 23, 24 and 25, 1957, at the Ambassador Hotel, Los Angeles, California, and the second paper at the Association for Computing Machinery Session of the Indianapolis meeting of the American Association for the Advancement of Science on December 28, 1957.

The first paper is descriptive, covering the major developments in programming for numerical control up to the present day. The "APT System" is introduced for combining the human designer, the general purpose computer, and the numerically controlled machine tool for production of complex parts. The second paper is primarily

tutorial, describing the philosophy behind the current research developments. The "systematized solution" concept, which is the distinguishing feature of the recent work, appears to be applicable to problem solving in other fields as well as numerical control.

10. Technical Memorandum 6873-TM-4, Operation of the M. I. T. 2D-APT II Systems Tape, Clarence G. Feldmann, July 1, 1958, 5 pp. (Limited distribution)

This memorandum contains operating instructions for running a version of the APT system stored on magnetic tape at the M. I. T. Computation Center 704 computer.

11. Technical Memorandum 6873-TM-5, Proposed Development of Whirlwind APT II and APT III, Robert Polansky, August 14, 1958, 19 pp. (Limited distribution, reproduced as Appendix C of Interim Report 6873-IR- 6 and 7, see item 4 of this list)

At the time of this memorandum, APT II and APT III computers were being simulated by programs on the M. I. T. Whirlwind Computer. The memorandum describes difficulties with the programs, proposed solutions, and plans for linking the two systems.

12. Technical Memorandum 6873-TM-6, Curvilinear Interpolation, Steven Brambrut and Jack Weinberg, August 28, 1958, 20 pp. (Limited distribution)

This memorandum describes the results of a preliminary investigation of approximating space curves by parabolic interpolation. For the analyses presented, the APT II system is assumed to provide the unit normal of the surface program, the tangent vector of a space curve program, the radius of curvature program, and the iteration scheme for locating a point on the curve. A method for modifying the M. I. T. machine tool director for parabolic interpolation is given.

13. Technical Memorandum 6873-TM-7, Output Oscilloscope Program, Jerome R. Wenker, September 22, 1958, 14 pp. (Limited distribution, reproduced as Appendix B of Interim Report 6873-IR-6 and 7, see item 4 of this list)

This memorandum describes an IBM 704 program to calculate and plot pictures on the scope attachment (IBM Unit No. 740). The program will produce true perspective pictures of any line or series of lines, including coordinate axes.

14. Technical Memorandum 6873-TM-8, Curvilinear Interpolation, Steven Brambrut, February 16, 1959, (Thesis Proposal), 9 pp. (Limited distribution)

This memorandum proposes a design of a curvilinear interpolator to be used as part of the APT computer. This interpolator essentially performs the same functions as the arithmetic element of the present APT computer.

In order to use a digital device in real time, a means is being sought to improve upon the relatively slow speed of a general-purpose computer. Investigation of digital differential analyzers -- DDA's -- to perform the necessary calculations is currently being studied and is reported upon in this memorandum. The proposed system described here will be simulated using a general-purpose computer. In this way the accuracy of the system can be determined and experimentation with the proposed techniques can be undertaken.

15. Technical Memorandum 6873-TM-9, A Digital Computer Method for Simple English Sentences, Clarence G. Feldmann, July 1959 (Master's Thesis), 71 pp. (Full distribution)

The purpose of this thesis is to present a method of conveying meaning to a digital computer by means of simple English sentences. The basic method used is to transform the sentences into a numerical "meta-language" which is more natural and convenient for use by the computer. During the transformation process, the information contained in the sentences is considered to pass through various "language levels." The numerical meta-language is the final level in this process. The major level transformation is from grammatical structure patterns into "thought groups." This jump is accomplished through processes analogous to several mathematical analysis techniques. Once the transformation from English to meta-language has been completed, the information being conveyed is in a form which may be easily used by computer logic routines to control the operation of computer calculation routines or to be retranslated back into other languages.

Since the primary aim is a real communication of thoughts and not a complete translation scheme for the entire English language, the allowable forms of English sentences which may be used have been restricted. These restrictions allow the use of only the more regular and rule-obeying forms of sentences, while still allowing a great deal of flexibility. In this way, such complex considerations as subjunctive moods, idiomatic expressions, etc., are eliminated, and the main task of conveying meaning is stressed.

As demonstration of its usefulness, the method is applied to the controlling of a large computer routine known as the APT II system. The computer program and corresponding flow charts for this application of the method are presented as the final section of the thesis. A great deal of further research may be done in relaxing the restrictions as to sentence types as well as in applying the method to other areas of work. The thesis contains a section in which several such areas of future research are described.

16. Technical Memorandum 6873-TM-10, Requirements for a Curvilinear Interpolator Using Incremental Computation, Steven A. Brambrut, September 1959 (Master's Thesis), 125 pp. (Full distribution)

The use of curvilinear interpolation in numerical control of machine tools is a relatively unexplored topic. Directors have been built which perform parabolic interpolation. These directors are most effective when cutting planar curves. Unfortunately, when an automatically programmed tool system is used to determine the individual cuts, parabolic or any other interpolation in which a single prescribed type of tool motion is used to approximate the curve, it makes the computer program considerably more complex. The interpolator of this thesis not only enables curvilinear interpolation, but simplifies the data processing problem.

The DDA is an appropriate real-time device to use in the computation process for two reasons. Its incremental properties make it compatible with existing numerically controlled tool systems, and the DDA can be programmed easily.

This memorandum first describes the characteristics of DDA's and explains how they are programmed and scaled. It then describes the use of DDA's to perform curvilinear interpolation. A TX-0 computer program was written and used to simulate the curvilinear interpolator. The results of several examples are tabulated and analyzed. The parts of these examples were cut to within 0.0013 inch.

17. Technical Memorandum 6873-TM-11, Adaptive Control of Curve-Following Devices, Carl E. Nielson, Jr., September 1959 (Master's Thesis), 51 pp. (Full distribution)

Current tracer-controlled milling machines operate with a single probe sensing the template and have a fixed system response which cannot be optimum for certain template shapes. This memorandum investigates the feasibility of utilizing additional probes to obtain future information from a template of the desired surface, to permit the system response to be varied (adapted) so that optimum following is achieved. A mathematical model of a tracer-controlled milling machine is assumed and the adaptive control theory developed by Merriam is applied to determine the optimum control configuration for the system for two cases. First, it is assumed that an exact knowledge of the future desired response is supplied to the system and the optimum response is found for various combinations of the parameters of the system. Physically, however, an exact knowledge of all future values of the desired surface cannot be supplied to the system. The major objective of this memorandum, therefore, is the development of a method whereby the optimum response is closely approximated using a simplified probe arrangement on the desired surface. The multiple probes measure specific values of the desired response and supply this information continuously to a simple realization of the optimum control configuration. An analog computer was used to simulate the mathematical model and study its response to various inputs and conditions.

18. Technical Memorandum 6873-TM-12, Automatic Selection of Initial Values for Iterative Procedures, Robert B. Polansky, September, 1959, (Master's Thesis) 47 pp. (Full distribution)

This report describes a method for selecting initial or starting values for iterative procedures. The problem which this method solves, when used with an appropriate iterative procedure, is that of finding the zeros of arbitrary functions of N variables. Provision is also made for simultaneously satisfying auxiliary constraints of the type $G(X_1, \dots, X_N) \geq 0$ and auxiliary conditions of the type $H(X_1, \dots, X_N) = 0$ where X_1, \dots, X_N are the variables of the arbitrary given function.

Many iterative procedures are known for finding zeros. However, these procedures require values which satisfy the following specifications:

1. The iterative procedure converges when started from any of the initial values.
2. The points of convergence will be different for different starting points.
3. If a zero exists in the particular region being examined, then the iterative procedure will converge to this zero when started from one of the selected initial values.

The method of obtaining initial values, which is described in this report, is a generalized scanning procedure. A program which uses this method for selecting initial values has been written for the IBM 704 digital computer. The results of several test cases, successfully run on the M. I. T. Computation Center 704, are also presented.

19. APT Volume I, General Description of the APT System, Douglas T. Ross, June 1959, 85 pp.

As the name implies, this report contains a general description of the APT concept, a brief review of the system operation, and plans and possibilities for future development. The standards established for organization of the APT Manuals and procedure for future changes are explained, as well as the AIA APT Project Procedures.

20. APT Volume II, APT Part Programmer's Manual, Douglas T. Ross, May 1959, 130 pp.

This report describes in detail the language facilities which are available in the APT system. Sample part programs are worked out completely to illustrate how the language is used, and a number of specialized part programming techniques are also illustrated.

21. APT Volume IV, A Description of the APT Computer Programs, by authors from M. I. T. and participating AIA companies, May 1959, 162 pp.

This report contains detailed writeups of all the various computer programs which compose the APT system. Detailed flow diagrams are given and coding details are emphasized. The initial volume contains descriptions of how the system has been coded for the IBM 704 computer, and additional volumes parallel in structure will probably be required to document the equivalent programs coded for other computers.

22. APT Volume V. Operator's and Troubleshooter's Manual, Clarence G. Feldmann, May 1959, 27 pp.

This report contains information concerning operation of the system on the computer. It is hoped that as the APT system is put into routine use in more and more production facilities, the operating techniques for each of these procedures will be described in this volume. It is of course possible to operate the programs in many different ways setting up magnetic storage differently, using so-called off-line input techniques, and operating the programs either manually or automatically. By having representative writeups of the various possibilities, the user can choose that method most appropriate to his own installation. The troubleshooter portion of this volume concerns listings of diagnostic information printed out at the various error stops in the program. The check list will prove helpful to the operator during the running of the system, as well as to the computer programmer in off-line debugging procedures. Where the system is as complex as the APT system, especially if allowance is made for its future expansion, efficient procedures for system maintenance in terms of the programs, themselves, becomes increasingly important. It is hoped that as experience is gained with the system, this volume will grow in comprehensiveness and usefulness.

23. APT Volume VI, Modification and Change Procedures, Clarence G. Feldmann, May 1959, 54 pp.

This report describes the various changes to the programs which must be made for the more important standardized additions which are expected to be made to the system. Such things as adding words to the vocabulary, inserting new surface types and other changes, which represent a horizontal rather than a vertical expansion of the system, are spelled out in great detail. Using this volume it is an easy matter for the individual user of the APT system to increase and mold its capabilities to suit his own needs. This volume also provides a useful adjunct to the earlier more descriptive volumes in that by collecting all of the aspects of the various programs concerned with one topic under one heading, it can be of great assistance to the computer programmer in obtaining an overall view of the entire collection of computer programs.

24. APT VII, Group Control for Automatic Manipulation of Computer Programs which Exceed Core Memory, David McAvinn, December 1959, 59 pp.

A frequently encountered problem in computer usage is what to do when a program outgrows the capacity of core memory. The programmer must divide the program into segments small enough to fit into core memory, and arrange for each segment to be transferred from tape or drum storage to core memory when needed. A program which performs the required transfers of memory segments and of the computer control automatically is called a group control program. With group control, the programmer can write his program as if the entire program was in core memory, and then adapt it for operation by simple patch coding. This report describes the Group Control Program which has been developed for the Automatically Programmed Tool (APT) system of programs, using the IBM 704 Computer. In addition to the GC program, a system of loading programs is described. The Loading Programs place the segmented program into auxiliary storage of the computer in a form suitable for GC operation. Although written especially for APT, these programs are suitable for general use and are available for the SHARE library.

25. Bibliography on Numerical Control of Machine Tools, compiled by A.K. Susskind, February 1, 1957.

This bibliography, prepared to assist those interested in reviewing the numerical control field, lists M. I. T. reports and papers issued in the period 1949-1957, articles and papers not authored by M. I. T. but based on M. I. T. developments, and important papers from other sources on numerical control developments.

26. Course Outline and Workbook for the Special Course on Programming for Numerically Controlled Machine Tools, given by M. I. T., March 25 to April 3, 1957. Prepared by M. I. T. personnel and authors from industry. (Distributed only to course attendees)

Contains sections on principles of numerical control, manual programming, problem analysis and data processing, economics, and problems associated with the introduction of numerical control into aircraft plants.

27. Selected References for the Special Course on Programming for Numerically Controlled Machine Tools. (distributed only to course attendees)

A collection of reference material culled from earlier project publications, M. I. T. summer course notes, and some items of this bibliography.

28. An Outline of Subject Matter for Industrial Training Programs in Numerical Control of Machine Tools, prepared by working groups at the March 25 to April 3, 1957 Special Course. (General distribution)

As part of the course, the participants undertook the formulation of an outline which might serve as a guide to industrial organizations planning to set up company training programs in Numerical

Control, with emphasis on familiarization, programming, and data processing. The outline is presented in this leaflet.

29. Report 6873-FR-3, Final Report on Automatic Programming of Numerically Controlled Machine Tools, for Period June 1, 1956 to November 30, 1959, J. E. Ward, January 1960. *

C. ARTICLES AND PAPERS BY M. I. T. PERSONNEL

1. "Automatic Programming of Numerically Controlled Machine Tools," Arnold Siegel, Control Engineering, Vol. 3, No. 10, October, 1956, pp. 65-70.
2. "Digital Information Processing for Machine-Tool," A. K. Susskind, IRE 1957 National Convention, Published in Part 4 of the Convention Record, pp. 145-149.
3. "The Economics of Work Performed on a Numerically Controlled Machine Tool," T. V. Atwater, Jr. and R. H. Gregory, Journal of Engineering, Vol. 8, No. 6, November-December, 1957, pp. 337-352.
4. "Some Recent Developments in Automatic Programming for Numerically Controlled Machine Tools," Douglas T. Ross, given at the Third Annual Contour Machining Conference, Los Angeles, California, October 23, 24, and 25, 1957. (No conference proceedings, paper is contained in Technical Memorandum 6873-TM-3, see item B-9)
5. "Numerical Control of Machine Tools," Donald F. Clements, talk delivered to the American Society of Tool Engineers, Fairfield, Connecticut, Chapter No. 6, Milford, Connecticut, December 4, 1957. (Not published)
6. "Development of a Research Effort in the Automatic Programming of Numerically Controlled Machine Tools," Douglas T. Ross, Association for Computing Machinery Session of the Indianapolis meeting of the American Association for the Advancement of Science, December 28, 1957. (No conference proceedings, paper is contained in Technical Memorandum 6873-TM-3, see item B-9)
7. "Developments in Automatically Programmed Tool Systems (APT)," Douglas T. Ross, Boston Section of the American Institute of Electrical Engineers, Boston, Mass., March 25, 1958. (Not published)

* In order to differentiate the final reports on the three major phases of contract AF-33(038)-24007, the new designation FR, for Final Report, has been added to the documentation series. The two previous Final Reports issued in September, 1952 (Appendix B) and March 15, 1956 (Appendix A) were originally published without report numbers, but will now be identified as Report 6873-FR-1 (in two parts) and 6873-FR-2, respectively.

8. "Principles of Numerical Control," D. F. Clements, Numerically Controlled Machine Tool Conference, Ordnance Weapons Command, Rock Island, Illinois, September 24, 1958. (Not published)
9. "A Progress Report on the 2D-APT-II Joint Effort for Automatic Programming of Numerically Controlled Machine Tools," Douglas T. Ross, ASME Paper No. 58-A-236, ASME Annual Meeting, November 30 - December 5, 1958, N. Y. (Published in condensed form in Mechanical Engineering, Vol. 81, No. 5, May 1959, pp. 59-60 and 70.) See also Interim Report 6873-IR-6 and 7, item B-4.
10. AIA-AMC-MIT APT System Press Conference (official release of the system), M. I. T. February 25, 1959. (See Appendix C for details of program and speakers.)
11. "The Future of Numerical Control," Douglas T. Ross, Conference on Numerical Control in Industry, Purdue University, April 7-10, 1959. (Not published)
12. "Description of the APT System," Douglas T. Ross, International Conference on Machine Tool Automation, Prague, Czechoslovakia, September 1959. (To be published in Conference Proceedings)
13. "A Panel Discussion of the Significance of the Automatic Electronically Controlled Factory," moderated by Douglas T. Ross, IRE Northeast Electronics Research and Engineering Meeting, Boston, November 17, 1959. (To be published in the NEREM-1959 Proceedings)
14. "Description of the APT System for Automatic Programming of Machine Tools," Clarence Feldmann, IRE Northeast Electronics Research and Engineering Meeting, Boston, November 18, 1959. (To be published in the NEREM-1959 Proceedings)
15. "The Design and Use of the APT Language for Automatic Programming of Numerically Controlled Machine Tools," Douglas T. Ross, Sixth Annual Computer Applications Symposium, Armour Research Foundation of the Illinois Institute of Technology, Chicago, Illinois, October 29, 1959. (To be published in the Proceedings of the Symposium)

APPENDIX A

The previous final report on Contract AF-33(038)-24007, which covers the period from 1951 to 1956, describes the design, development, and evaluation of a numerically controlled milling machine. The report is still much in demand and has been included here for reference purposes.

As explained in the footnote on page 58, the number 6873-FR-2 has been recently assigned to this report for identification purposes.

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Design, Development and
Evaluation of

A NUMERICALLY CONTROLLED MILLING MACHINE

Final Report

March 15, 1956

Approved:


J. O. McDonough

Servomechanisms Laboratory
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This document reports the results of work made possible through the support extended the Massachusetts Institute of Technology, Servomechanisms Laboratory, by the United States Air Force, Air Materiel Command, under Contract No. AF33(038)-24007, M. I. T. Project No. D.I.C. 6873. It is published for technical information only and does not represent recommendations or conclusions of the sponsoring agency. When U. S. Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related U. S. Government procurement operation, the U. S. Government thereby incurs no responsibility or obligation whatsoever; and the fact that the U. S. Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation or conveying any right or permission to manufacture, use, or sell any patented invention that may be in any way related thereto.

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CHAPTER I

INTRODUCTION

The numerical control program at the Servomechanisms Laboratory began in July 1949 under the sponsorship of the Parsons Corporation of Traverse City, Michigan, and the U.S. Air Forces. The first phase of this program consisted of a study of numerical control and its possible application to machine tools. A wide range of practicable machine-tool systems was considered. One of these systems was selected for detailed study. A milling machine was chosen as a convenient example of a tool which could be adapted to three-axis numerical control. A report covering complete design and performance specifications of this system was completed in June 1950. Soon thereafter, a program was initiated to construct an experimental machine-control system as outlined in the study report.

In February 1951, when construction of the system was approximately 30 percent complete, the Parsons Corporation terminated its sponsorship of the program and the Air Materiel Command of the U.S. Air Forces assumed direct financial responsibility. In March 1952, construction of the numerically controlled milling machine was completed and in September of that year, it was demonstrated formally to representatives of the aircraft industries, machine-tool builders, and others.

Between April 1952 and May 1955, the Servomechanisms Laboratory under Air Force sponsorship carried on a program to expand the understanding and utilization of numerical control. This program has included:

- (1) Studies of the application of numerical control to other machine tools and manufacturing systems.
- (2) Studies of electronic systems and components pertinent to numerical control.
- (3) A program of machine testing and evaluation.
- (4) A program for the development of techniques for the use of numerically controlled machine tools, notably in the areas of programming techniques.
- (5) An information-dissemination program to aid industrial understanding and utilization of numerical control.

In July 1953, the Servomechanisms Laboratory with the approval of the U.S. Air Forces initiated a project to develop and build an industrial prototype machine-control system under the sponsorship of the Giddings and Lewis Machine Tool Company of Fond du Lac, Wisconsin. The equipment built under this project was delivered to Giddings and Lewis in May 1955. Its design avoids many of the serious shortcomings which had become evident in the Air Forces experimental machine during the evaluation program.

During the spring of 1955, the Air Materiel Command decided to sponsor no further work by the Servomechanisms Laboratory in the areas of system studies, component studies, or information dissemination, because of the industrial interest then apparent and of the manifest ability of industry to carry on these phases of activity without Air Force aid. Since that time, the project activity has been limited to closing out and preparing reports on the various programs and studies now terminated.

Plans are underway, however, for a continuation of the study at the Servomechanisms Laboratory of programming techniques applicable to numerically controlled machine tools.

This report covers briefly all the work performed in the numerical control program, presents a list of abstracts from all published documents, and lists all files of the project containing basic information or documents of historical value.

CHAPTER II

HISTORY OF THE PROJECT

A. THE PARSONS' CONTRACT

The original contract with the Parsons Corporation provided for research from July 1, 1949 to June 30, 1950, but was extended by mutual consent. The field of research was in two phases. Phase I was to be an engineering study directed toward the development of a system, applicable to machine tools, for controlling the position of shafts in accordance with the output of a computing machine.

Phase II called for supplying an apparatus to operate a demonstration machine tool. The work contemplated was the manufacture of integrally stiffened wing skins. Surface finish must have no roughness in excess of .001 inch and must be correctly located within .003 inch when operating at a conventional table-feed rate.

Because of the general specifications as to type of machine tool, feed speeds, accuracy, power requirements, etc. the initial approach was to assume a system broadly along the lines of the block diagram of Fig. 1. Thus some form of computer would receive data describing the desired work and would convert these data into a continuous set of signals representing the desired cutting-tool position. Then some form of servo-mechanism would continuously attempt to make the actual position of the cutter coincide with its signalled desired position. It is also possible that actual tool position data would be helpful to the computer in calculating the desired position.

The immediate problem encountered was the development of a practicable means of specifying desired tool motion for the general case of large sculptured pieces such as integrally stiffened wing skins. An analysis of the problem of converting work-surface specifications into tool-motion specifications indicated the need for two kinds of mathematical operations, namely: interpolation and tool-offset computation.

For simplicity without limiting the capabilities of the system, a spherical cutter was assumed. In this case, the locus of desired tool-

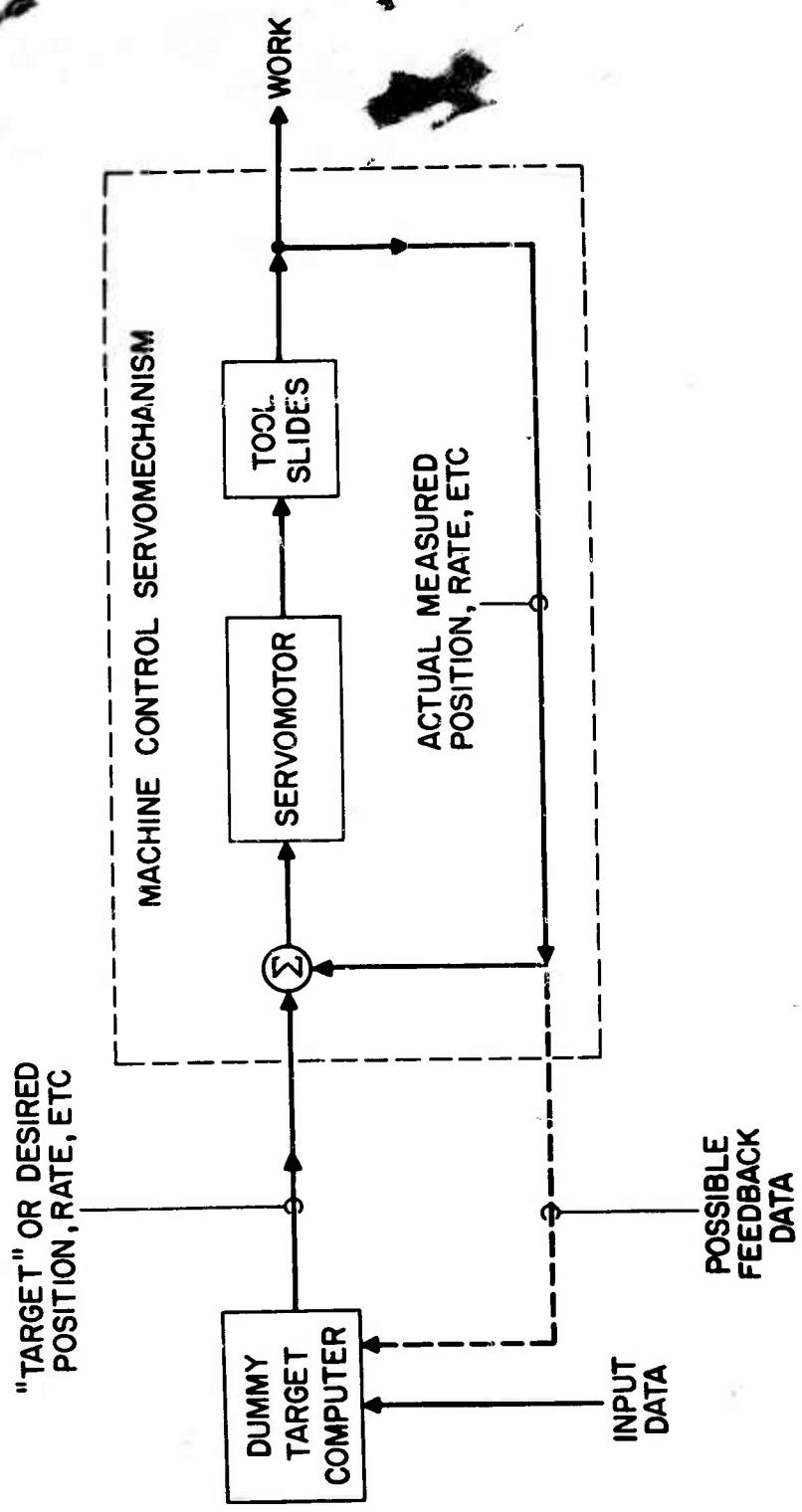


Figure 1. Block Diagram of Basic Machine-Tool Control

center positions is a surface parallel to the desired work surface except that it must never be re-entrant. Such a tool-center locus has, at every point, the same slope as the work surface at the corresponding point. Since interpolation can yield values of the slope of a desired surface at every point between given points, it is theoretically possible to finesse the tool-offset computation. Two important practical difficulties arise, however. One is the re-entrancy requirement stated above, the other is the fact that the derivation of a surface from its slope data involves the process of integration and all known physical integrators exhibit a drift characteristic far in excess of the accuracy required of an automatic machine tool. Thus frequent check points are required on the tool-center locus.

The re-entrancy requirement can be eliminated if it is specified that the desired work surface never have concavities whose minimum radius of curvature is less than the tool radius. Unfortunately the computation of fillets to replace inside corners and other localities where trouble might occur is basically the same computation as the calculation of the tool-center offsets at those points.

Thus it is practically impossible to avoid the tool-offset problem. It remains to choose an economical method of calculating tool offsets. Since it was expected that tools would run as high as 8 inches in diameter, and that the desired accuracy would be 0.008 inch, most analog computation equipment was immediately eliminated. A detailed examination of the mathematics of the problem indicated that special-purpose digital equipment of the time was likely to be less economical than a general-purpose digital computer. It was therefore decided that the tool-offset computations would be performed external to the system.

A similar investigation of the interpolation problem quickly ruled out the possibility of including within the system means for general three-dimensional interpolation of any order on unequally spaced data. A simple, practical means was, however, developed for linear interpolation between two given points in n dimensions. This was the frequency divider described elsewhere in the project literature.

The next serious problem encountered was the position-feedback instrumentation. An accuracy of approximately 0.003 inch out of approxi-

mately 100 inches was desired as well as a sensitivity of 0.0005 or better. It was determined that the normal elastance and wear on a reasonably sized main drive screw would preclude its use as a primary measuring element even if compensating cams were used. Among the alternate suggestions studied were the following:

- (1) A linear coded commutator with sliding brushes.
- (2) A linear non-coded commutator with sliding brushes and accumulating counter.
- (3) An interferometer device designed to count fringes.
- (4) A linear grating with a microscope to allow photoelectric counting of the lines as they passed.
- (5) A linear grating passing by a fixed grating of slightly different spacing so that a vernier effect would be achieved.
- (6) The use of a servo-driven auxiliary instrument screw with some form of angular encoder.

While any of these devices could conceivably have been made to work satisfactorily, each had fairly serious disadvantages and the device finally settled on was a simple 120-bar commutator with three brushes staggered to provide 360 contact points per revolution. A simple electronic system called the position code converter translates the brush signals into a single electrical pulse for each degree of rotation. The pulses are delivered to the remainder of the system over one of two lines, depending on the direction of the rotation.

With the development of an interpolator capable of transmitting one pulse for each desired distance increment and an instrumentation system capable of transmitting one pulse for each distance increment accomplished, the need arose for an error-detecting system. Such a system must accept command pulses and feedback pulses, each on either a plus or a minus line, and develop a continuous voltage proportional to the integrated algebraic difference of the two. The simplest means found to accomplish this end was the summing register and decoder described elsewhere.

The remaining problems in the development of a workable system were chiefly questions of convenience which were reasonably settled by July 1950. At that time project effort was shifted entirely from a basic study of possible alternatives to the detailed design and development of a

single working system.

By December 1950, most of the preliminary breadboard work had been completed and the project effort had shifted largely to the construction of equipment for a trial one-axis system.

B. AIR FORCES' BASIC CONTRACT

At the end of January 1951, the Parsons Corporation terminated its sponsorship of the project and the A. M. C. of the U.S. Air Forces undertook direct support of the work. The construction of a one-axis system was approximately 60 percent complete at this time.

During July 1951, a complete automatic control system for the first axis of the milling machine was assembled. The machine table was operated in response to test commands on punched paper tape. Work was started immediately on the manufacture of components for operating the second and third axes.

In September 1951, the first steps were taken toward broadening the area of investigation under the project. While primary emphasis remained on the completion of a three-axis milling machine system, the following studies were initiated:

- (1) Study of the most promising application of numerically controlled machine tools.
- (2) Development of computation techniques to facilitate preparation of machine-control tapes.
- (3) Checking studies.
- (4) Study of measuring and coding devices.

At approximately this time, the laboratory began to receive a steady stream of visitors interested in numerical control.

In March 1952, the construction of an operating three-motion milling-machine system was completed. Several pieces were cut by the machine under full tape control.

As the construction phase of the project drew to a close, a series of discussions was held with representatives of A. M. C. concerning the disposition of the machine-tool system. It was decided that the Servo-mechanisms Laboratory should keep the machine and initiate a program to evaluate it. This program was set up in three parts:

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- (1) Machine Operations - a program to operate the tool under conditions approximating those to be met in industry so that data could be obtained on:
 - (a) Productivity.
 - (b) Economy.
 - (c) Accuracy.
 - (d) Group organization and operating procedure.
 - (e) Computation methods.
 - (f) Machine availability time.
 - (g) Reliability.
- (2) System Studies - a program to investigate aircraft tooling and production processes to determine the most promising applications of numerical control.
- (3) Component Studies - a program to investigate better components and sub-systems for numerical control systems as the need was indicated by the machine operations or systems studies.

C. AIR FORCES' SUPPLEMENTAL CONTRACT

In May 1952 a supplement to the original Air Forces contract was issued to cover this work.

Left over at this time from the original contract was an obligation to hold comprehensive demonstrations of the numerically controlled milling machine for representatives of the aircraft and machine-tool industries. These demonstrations which were held in September 1952, developed into the first step of a fourth continuing program, under the title of Liaison Activities.

While in many cases the dividing lines between the four concurrent programs were vague and indefinite, it is convenient to present the remaining history of the project under the four separate headings. The approximate distributions of engineering effort were as follows:

| <u>Year</u> | <u>Percent of Machine Operations</u> | <u>Percent of System Studies</u> | <u>Percent of Component Studies</u> |
|------------------|--|--------------------------------------|---|
| 1952 (11 months) | 46 | 7 | 38 |
| 1953 | 44 | 20 | 36 |
| 1954 | 41 | 23 | 36 |
| 1955 (6 months) | 29 | 49 | 22 |

1. Machine Operations

This program included all of the work directly associated with the manufacture of various numbers of approximately 76 different pieces. Thus, in the beginning, the basic studies of programming techniques were included under this heading, but as soon as effective techniques had been developed and were in use, further efforts in the development of programming methods were carried under system studies.

During the major portion of this study, two full-time programmers and one computer were assigned to the programming tasks. One programmer was usually an engineer new in the project group, as the programming of a piece was often used as the means of initiating him into the work of the project.

During the entire project, a daily log of machine utilization was maintained. The 10,700 hours of operation registered by the running-time meter have been distributed as follows:

| | <u>PERCENTAGES</u> | | | | | |
|---------------------------------|--------------------|-------------|-------------|-------------|-------------|--------------|
| | <u>1951</u> | <u>1952</u> | <u>1953</u> | <u>1954</u> | <u>1955</u> | <u>Total</u> |
| Engineering Test | 15 | 53 | 15 | 6 | 26 | 25 |
| Program Test | No record | 4 | 9 | 13 | 9 | 8 |
| Work Setups | No record | 5 | 12 | 7 | 3 | 7 |
| Metal Cutting | 11 | 14 | 25 | 28 | 21 | 21 |
| Preventive Maintenance | No record | 3 | 6 | 4 | 2 | 3 |
| Repair of Trouble | 41 | 3 | 7 | 2 | 3 | 7 |
| Miscellaneous | 33 | 18 | 26 | 40 | 36 | 29 |
| Approximate Total of Test Hours | 1500 | 2600 | 2300 | 2300 | 2000 | 10,700 |

Engineering Test includes all work done to evaluate the system, such as the determination of power-supply margins, evaluation of the factors contributing to work-surface waviness, and transient-response tests on the servomechanisms. Also under this heading is time during which the machine tool or director was used as a test instrument for other equipment, such as breadboard assemblies. Generally speaking, engi-

neering test time was productive time which necessitated approximately as much setup as metal cutting.

Program Test is all time used in checking machine-control tapes. Typically, this time is made up of one run or more in which the tape is run through the director alone, and one final run in which the milling machine carries a dummy tool over an actual workpiece before metal cutting is begun. In 1951, this time was included under the heading of Metal Cutting.

Work Setups includes time spent by the machine operator in studying instructions, setting up and disassembling fixtures on the machine, and setting up and removing individual workpieces. In 1951, this time was included under Metal Cutting.

Metal Cutting means both manually controlled and tape-controlled cutting.

Preventive Maintenance covers operations which should be performed at reasonably regular intervals, but which can always be postponed until the end of the present production run if necessary. Typical operations are cleaning or replacing oil filters, routine electron-tube tests, cleaning coder drums, etc. Since the system was new, no time was logged against this item in 1951.

Repair of Trouble tabulates all time spent in the diagnosis and treatment of any condition which, in the opinion of the operating or maintenance personnel, threatens the safe or effective use of the system for the work at hand. Time spent testing the system after the correction of a trouble is also noted. Approximately two thirds of the trouble time has been due to failure of mechanical equipment and one third has been due to electrical and electronic equipment trouble.

Miscellaneous consists of chiefly time during which power was on, hence the running-time meter was running, but the system was idle. Also included here is time spent on demonstrations for which the system was operated, but no metal was cut.

An examination of the total statistics reveals some rather striking facts. The system had outgrown its initial high-maintenance period by the end of 1951, which was even before its three axes were completed. If the figures are recalculated, omitting 1951, the Repair of Trouble for 1952 through 1955 amounts to 3-2/3 percent and Preventive Maintenance to 3-1/3

percent. Engineering Test and Metal Cutting together amount to approximately 48 percent of total time. If work could have been scheduled with No Idle Time, and if the ratio of productive time to setup and program tests was the same as that shown, total machine utilization for 1952 through 1955 would have been distributed as follows:

| | <u>ACTUAL</u> | | <u>RECALCULATED</u> | |
|------------------------|---------------|---------|---------------------|---------|
| | Recorded Time | Percent | No Idle Time | Percent |
| Productive Time | 4366 | 48 | 6439 | 70 |
| Program Test | 795 | 9 | 1172 | 13 |
| Setup | 628 | 7 | 925 | 10 |
| Preventive Maintenance | 315 | 3.33 | 315 | 3.33 |
| Trouble | 349 | 3.67 | 349 | 3.67 |
| Idle | 2747 | 29 | 0 | 0 |
| Total | 9200 hrs. | 100 % | 9200 hrs. | 100 % |

Thus this fully automatic, experimental machine working on piece runs that never exceeded 12 pieces at a time and averaged 2 or 3 pieces at a time showed actual down time for all maintenance of only 7 percent and actual productive time three times the actual total non-productive setup time. Potential time was 70 percent of total time.

2. System Studies

System studies included both the study of the applicability of numerical control to machines other than the M.I.T. milling machine and the study of the productive-system aspects of the M.I.T. machine.

Under the former category it developed that the most constructive approach was to act as a general consultant to industrial firms who were investigating various applications of numerical control. Among those firms who made use of this service were:

Aeroproducts Division of General Motors Corp., Dayton, Ohio
 Boeing Airplane Co., Seattle, Washington
 Bridgeport-Lycoming Division of Avco, Stratford, Connecticut
 The Bullard Co., Bridgeport, Connecticut
 The Carborundum Co., Niagara Falls, New York

Convair Division of General Dynamics, San Diego, California
Curtiss Wright Corp., Wood Ridge, New Jersey
Designers for Industry, Cleveland, Ohio
Douglas Aircraft Inc., Santa Monica, California
E. I. DuPont De Nemours & Co. Inc., Wilmington, Delaware
Ferranti Ltd., Edinburgh, Scotland
General Riveters Inc., Buffalo, New York
Giddings and Lewis Machine Tool Co., Fond du Lac, Wisconsin
Kaiser Metal Products, Bristol, Pennsylvania
Arthur D. Little Co., Cambridge, Massachusetts
Lockheed Aircraft Corp., Burbank, California
The Glenn L. Martin Co., Baltimore, Maryland
North American Aviation Inc., Los Angeles, California
Norton Co., Worcester, Massachusetts
Oerlikon Tool and Arms Co., Asheville, North Carolina
Stanford Research Institute, Palo Alto, California
Thompson Products Inc., Cleveland, Ohio
Ultrasonic Corp., Cambridge, Massachusetts

Of the above 23 companies, nine now have active projects in the field of numerical control. An outgrowth of this program was a contract between M. I. T. and the Giddings and Lewis Machine Tool Co. for the development of a commercial prototype numerical-control system under Giddings and Lewis sponsorship.

Under the general subject of the M. I. T. milling-machine system studies, the chief areas of interest were the economic and programming studies.

The economic study was the result of early attempts to compare the costs of producing pieces on the M. I. T. machine with the costs of producing the same pieces by conventional methods. Two areas posed problems which appeared insurmountable to the engineers on the project. First, it appeared to be impossible to obtain reasonable estimates of the cost of producing parts by conventional means even when these parts were actually in production, and second, it appeared to be impossible to obtain reasonable estimates of the costs, under normal industrial conditions, of the operations which we performed at M. I. T. when the pieces were pro-

duced by numerical control. Accordingly, members of the M. I. T. School of Industrial Management were approached for assistance in this study, and two of them agreed to undertake the study. This work, while falling far short of a definitive answer to the question of relative costs, succeeded in providing rough cost comparisons and in definitely pointing out the most profitable area for future work, to wit: programming.

The programming studies began early in 1951, when the input specifications for the M. I. T. system were frozen, and have run almost continuously since then.

Throughout the study, the development of both manual and machine methods of programming have proceeded side by side. No machined piece has yet been encountered which would be impossible to program for the numerically controlled milling machine and few have been found for which the programming effort could not have been reduced if the part had been specified in a more convenient form. As manual techniques of program were gradually developed to handle the pieces which we were studying, various portions of the programming operation were translated into sub-programs for the M. I. T. Whirlwind I Computer.

At the present time, most of the separate mathematical operations necessary to make machine-control tape for almost all parts are available as Whirlwind I subroutines. One major difficulty was encountered, however, in the use of these subroutines, namely that an experienced Whirlwind I programmer was needed to patch the subroutine together into a complete routine each time a new type of job was encountered. In addition, it was necessary for the human programmer to translate the drawing into exactly the kinds of information needed by the subroutines. For example, to specify cutter motion around a fillet of given radius tangent to two given lines, it was first necessary to calculate the locations of the center of the fillet arc and the two points of tangency. Often such calculations as this constituted the lion's share of the programming effort. Thus, complete as they were, the Whirlwind I subroutine library lacked general applicability. A study of commercial computing devices showed that this difficulty is also encountered by others in the field.

Late in 1954, a new approach to the above problem was initiated. In this study an attempt was made to program Whirlwind I to accept and

interpret a series of instructions presented in a limited, plain-English vocabulary. This study has been strikingly successful in the case of two-dimensional work. In many cases programming time has been reduced to one fifth of that previously required. It is now being proposed that the Air Forces sponsor the extension of these techniques to work involving three-axis and five-axis milling.

In addition to the above studies, minor work was done in the field of digital curvilinear interpolators which might be suitable for inclusion in a director system. These studies disclosed no system that appeared able to compete on economic grounds with the existing M.I.T. system for the typical work which we were encountering at the time.

3. Component Studies

Component studies fell roughly into two classes: studies of new components suitable for inclusion in numerically-controlled machine tool systems but not necessarily into the M.I.T. system and studies of components of the M.I.T. system in which there seemed to be room for improvement.

a. New Components

(1) Optical Grating Feedback-System

This system, consisting of a linear-grating which would pass by a fixed viewing station having four grating segments, was one of the earliest component studies undertaken. The study indicated that this system could directly replace the coder drum if it were desired to perform the decoding function in the power servomechanism. A position code converter essentially identical to that presently in use yields one output on either a plus or a minus line for each increment traveled. For measurements of a sensitivity of 0.0005 inch, no serious difficulty is encountered in the equipment.

(2) Optical Coder Drum

The same system as that above can be used in connection with a rotary coder drum for the decoding servomechanism. One of the advantages of this system is that it can be made much more sensitive than 0.0005 inch

for a system having feed speeds in the range of 15 inches per minute.

(3) Magnetic Core Studies

A general investigation into the applicability of various ferromagnetic elements to numerical control systems was started in late 1952. The most promising area for the use of magnetic elements in the M.I.T. system is in the data-storage system that now uses relays and stepping switches. Here two functions are required: the ability to receive and store data in serial form; and the ability to retain the stored data in the process of many interrogations.

Conventional magnetic stepping registers perform the first of the above functions through the use of two cores per digit. Two means for reducing this requirement to one core per digit were investigated: the use of short delay lines for temporary information storage, and the use of the hole-storage effect in semiconductor diodes for the necessary temporary storage. Both approaches appear feasible. A complete breadboard system using diodes was built and tested successfully.

In conventional magnetic storage elements, the stored information is destroyed in the process of a single interrogation. For use with a frequency divider, therefore, it is necessary to provide means for restoring the information after interrogation or for not destroying it in the process of interrogation. Here again the use of delay lines as temporary storage elements is feasible. The use of a second core per digit also provides a temporary parking space for the information. It is also possible to detect the state of magnetization of a core without demagnetizing it by interrogating all or a portion of the magnetic circuit with a flux which is orthogonal to the main flux. A complete breadboard system using this principle was developed and tested successfully.

(4) Optical Phase-Modulation Instrumentation

For systems that employ magnetic tape as an intermediate storage medium between the director and machine tool, it appears useful to use phase modulation of a low-frequency carrier to transmit the servomechanism control signals. Synchros may then be used as the servomechanism feedback instrumentation, but their use involves errors in measurement

which are not negligible, as is discussed below. In an attempt to develop an alternative to synchros, an optical grating system was designed which would give a 60-cycle (or any other convenient low frequency) phase-modulated signal with a sensitivity of one or two tenths of an inch per cycle. Preliminary analysis of the mechanical and optical errors which could be expected in the system indicated that the total mensuration errors would be approximately the same as those encountered with good synchros and good gearing. It was not possible to test this analysis before the end of the project.

(5) Phase-Modulation System

With the development of the Giddings and Lewis system in which a magnetic tape is used as intermediate storage, we had the opportunity to make some fundamental studies of the effect of magnetic tape on the system. We had complete information on the behavior of the M. I. T. machine and we had developed a quick and accurate means of analyzing the performance of the system. Therefore it was planned to use the magnetic-tape unit of the Giddings and Lewis system in conjunction with the M. I. T. machine to get some data to test our earlier theoretical analysis. Accordingly, a set of equipment capable of changing the M. I. T. machine to a phase-modulation system was designed and built. Simultaneously, a theoretical study of synchro errors in a phase-modulation system was carried out. Unfortunately because of the impending closing of this project and unforeseen delays in the completion of the Giddings and Lewis unit, it was not possible to carry out the desired study. Magnetic tape was successfully recorded, but no further work could be done.

b. Components of the M. I. T. System

(1) Pick-Off Brushes

From the very beginning, the mechanical coder drum-system was less than fully satisfactory. The design required that each brush should contact a single bar of the coder for only 0.030 inch for peripheral travel. It was therefore necessary to use brushes of very small, stable contact area. This requirement was met by the use of rollers, 3/8-inch in diameter.

At the maximum coder speed, each roller had to pass at least one of five or six electrical pulses presented to it. It was found that the successful operation of this system required careful attention to the cleanliness and lubrication of both the coder itself and the ball bearing rollers. An extensive series of tests on a breadboard coder succeeded in defining the problem without disclosing a satisfactory solution. In spite of the difficulty, the coder-drum maintenance only accounted for approximately 60 of the 350 hours of trouble time on the machine. It was therefore never necessary to junk the system and develop a better one.

(2) Finish Studies

The work surface of the early parts produced by the M.I.T. milling machine showed two distinct forms of waviness. One form was a very regular series of hills and valleys that appeared whenever the machine was cutting a surface perpendicular to one axis. This waviness varied from approximately 0.0002 inch peak-to-valley in the head axis to approximately 0.002 inch cutting a surface perpendicular to one axis. This waviness varied from approximately 0.002 inch peak-to-valley in the head axis to approximately 0.002 inch in the cross-slide axis. It was the result of a steady-state oscillation, ranging in frequency from one half to one fifth cycle per second, which was observable in any axis that was standing still.

The other form of waviness was observed whenever a cut surface was the result of combined motions of two or three axes. This waviness was not visibly regular, its peak amplitude initially was approximately 0.002 inch, its period was low enough so that it did not register on a standard profilometer and in spite of much free advice to the contrary from our visitors, it was easily established that it was not the result of improper coolant, cutter tooth form, cutter speed, feed speed, work-holding fixtures or other usual machine variables. The investigations of the two types of surface waviness were carried on concurrently, but will be discussed separately below.

(a) Zero-Speed Oscillation

The power servomechanisms of the M.I.T. system have a velocity constant in excess of 2000. It can be shown that such a system, in the

presence of elastance and static friction in its output will have a small-amplitude steady-state oscillation at zero speed. The first attempt to remedy this effect was an attack on the static friction. A series of lubricants was tested in a search for one which would show a running friction as high as or higher than its breakaway friction. None was found.

The second attack was aimed at the elastance in the drive system. It was found that several elements of the system were deflecting unduly under load, notably in the cross-slide drive system which exhibited the worst oscillation. It was possible to stiffen some of these elements appreciably with the result that the amplitude of the oscillation was reduced to approximately 0.00075 in the cross slide and 0.0002 in the table axis. Since the cross-slide oscillation was still objectionable, a thorough system analysis was made and several means of altering the system to eliminate the trouble were studied. Two of these were tried. Both were successful in eliminating the zero-speed oscillation entirely and one also improved the instrumentation. The latter is the system now installed on the machine-tool cross slide.

(b) Two-Axis Waviness

The first problem encountered in the attack on this phenomenon was a means of measuring the waviness. The technique that eventually developed was to clamp a hardened and ground-steel straight edge at an angle on the machine table. A linear differential transformer (Metrosite) was mounted in the spindle in such a way that spindle motion perpendicular to the straight edge would actuate the Metrasite. A command was then inserted in the director to move the spindle parallel to the straight edge. The resulting Metrasite signal was then recorded simultaneously on magnetic tape and on a recording galvanometer. The Metrasite was calibrated by letting it ride over a piece of skin stock of known thickness. The galvanometer chart was used to measure the peak-to-peak irregularities, while the magnetic tape was used as a direct input to the Servomechanisms Laboratory REAC computer in analyzing the sources of waviness.

The REAC computer was connected to carry out a limited harmonic analysis of the Metrasite signal. The result was an indication of the signi-

ficant frequencies present in the waviness. Once these were identified, a search was made of the system to locate components that would contribute such frequencies. The chief disturbing frequencies turned out to be once-and twice-per-synchro revolution and once-per-rack tooth. An intensive study of each of these components allowed us to improve each materially with the result that peak-to-valley waviness was reduced to approximately 0.0005 inch.

Early in the study, an attempt was made to determine the effect of the quantization of the decoding-servomechanism output on surface waviness. At that time, the other disturbing effects were so large as to mask the quantum effect and no conclusions could be drawn. After the other effects had been reduced, it was planned to repeat these tests, but it was not possible to do so before the project closed.

On the basis of the experience gained in the finish studies, an analysis was made of the surface-waviness effect of synchro errors in a phase-modulation system. It was impossible to verify this analysis before the project closed.

4. Liaison Activities

With the expansion of project activities in early 1952 to include the system studies and machine-operation studies described previously, it became necessary to conduct a program of liaison with potential industrial users of numerical control. The objectives of this program were to acquaint members of the project in production methods and problems and to solicit sample workpieces for the machine evaluation studies. It immediately became evident that the achievement of these objectives would depend in no small part on the extent to which we were able to educate members of the companies we visited in the techniques, limitations and potential applications of numerical control.

Accordingly, the third objective, namely, dissemination of information on numerical control, was added to the program. Since 1952, key project personnel have had opportunities to visit a number of aircraft installations. Among them are:

Airesearch Mfg. Co., Los Angeles, California

Aeroproducts Division of General Motors Corporation, Dayton, Ohio
Boeing Airplane Co., Seattle, Washington
Bridgeport-Lycoming Division of Avco, Stratford, Connecticut
Chance Vought Aircraft Inc., Dallas, Texas
Convair Division of General Dynamics, San Diego, California
Curtiss Wright Corp., Wood Ridge, New Jersey
Douglas Aircraft Inc., Santa Monica, California
Hughes Aircraft Co., Culver City, California
Lockheed Aircraft Corp., Burbank, California
Marquardt Aircraft Co., Van Nuys, California
McDonnell Aircraft Corp., St. Louis, Missouri
N. A. C. A. Lewis Flight Propulsion Laboratory, Cleveland, Ohio
North American Aviation Inc., Los Angeles, California
Northrop Aircraft Inc., Hawthorne, California
The Glenn L. Martin Co., Baltimore, Maryland
Republic Aviation Corp., Farmingdale, Long Island, New York
Ryan Aeronautical Co., San Diego, California
Solar Aircraft Co., San Diego, California
Thompson Products, Inc., Cleveland, Ohio
Wyman-Gordon Co., Worcester and North Grafton, Massachusetts
In that time, the number of sample workpieces presented for study has exceeded our capacity for programming and analysis.

We have given talks and shown a twenty-minute motion picture of the M.I.T. system for approximately 80 groups at industrial plants and technical society meetings. During this period, approximately 30 organized groups and over 3000 visitors have seen the machine at M.I.T. Two special summer programs of two weeks duration have been given at M.I.T. While these were not sponsored by the project, they drew heavily on the knowledge and experience which had been gained in the prosecution of the project. The 60 students who attended each of these special programs represented all sections of aircraft, electronic, machine-tool, and other industries, and all parts of this country as well as several European countries.

REPRINT OF MARCH 1956 REPORT

CHAPTER III

PROJECT PUBLICATIONS

A. DESCRIPTION

During the life of this project, the following types of publication were issued.

1. Engineering Reports

These reports are intended to present the results of major investigations which are essentially complete. They are subjected to review for both content and presentation before publication. Several of the reports are adapted from student thesis reports. Eighteen Engineering Reports have been issued. Abstracts of Engineering Reports are given in Section B below.

2. Engineering Memoranda

These reports are intended to preserve interim data in a major investigation; to record the results of a minor investigation; or to get project dissemination of information of immediate need. They are not reviewed before publication. They are not available for distribution outside the laboratory, but a complete file is maintained by the project. There were 32 Engineering Memoranda issued.

3. Progress Reports

During Parsons' sponsorship of the project, regular Progress Reports were not required but starting after approximately four months, monthly reports were submitted anyway. Throughout the Air Forces sponsorship, monthly Progress Reports have been required and submitted. Copies of the Progress Reports are available for A.M.C. Seventy-five Progress Reports have been issued to date.

4. Job Analysis Reports

These reports are similar to Engineering Memoranda in intent. A

job analysis report is written for each machine job performed as soon as possible after completion of the job. Job Analysis reports are not reviewed. They are not available for distribution. A copy is filed with the job folder and a complete file is maintained by the project. The job analysis file, summarized in Engineering Report No. 17, was the source of most of the Servomechanisms Laboratory information in the economic study report, Engineering Report No. 18.

5. Special Publications

Two special publications have been issued by the project.

a. A Numerically Controlled Milling Machine.

This is a small brochure describing the operation of the system. It was issued just prior to the completion of the system to serve as a description for general distribution: 400 copies have been distributed since publication.

b. Final Report on Construction and Initial Evaluation of a Numerically Controlled Milling Machine.

This report is presented in three separately bound parts: Part 1; Part 2; and Appendix III to Part 2.

Part 1, 20 pages in length, is a small brochure that provides a non-technical description of numerical control. It was issued initially in connection with the formal demonstration of the M.I.T. machine in September 1952. Subsequent demands for this report were such that additional printings were required. A total of 2,483 copies has been distributed.

Part 2 is a complete technical description of the system and a manual on programming, operation, and maintenance of the system. It is available on request to A.M.C.* To date, 642 copies of Part 2 have been sent out.

Appendix III contains approximately 500 engineering drawings of the system. Thirty-three copies have been distributed.

* Requests should be directed to Commanding General, Air Materiel Command, Wright-Patterson Air Force Base, Ohio; Attention: MCPBMT.

B. ABSTRACTS OF ENGINEERING REPORTS

1. Engineering Report No. 1:

Physics of Metal Cutting and a Calculation of the Cutting Forces to be Expected on the Parsons Milling Machine

R. H. Marsh
October 18, 1949

This study was necessary to estimate the cutter-load requirements for a numerically controlled milling machine. It was based on the best data available at the time and is now obsolete.

2. Engineering Report No. 2:

Provisional Specifications for the Development of a Numerically Controlled Milling Machine

J. O. McDonough
June 30, 1950

The report contains descriptions of and provisional specifications for all essential components of the system. The specifications were intended as a guide to the development of these components. This report is superceded by Part 2, A Numerically Controlled Milling Machine.

3. Engineering Report No. 3:

Automatic Measurement of Lineal Motion Using Optical Gratings

J. H. Brown
June 12, 1951

In this report are described the design and construction of an experimental system using optical gratings for measuring lineal movement. Measurement consists, basically, of counting the number of grating lines that pass a reference point and recording this count in an electronic digital-counter. The mensural precision of this system is approximately 0.0005 inch. Several phototubes are used to observe the light passed through two optically superposed gratings. An interpreting circuit determines the direction and quantity of movement. The arrangement of the gratings to accomplish this and the effect of changing the line width of the gratings are described. The number of increments moved from some reference point is recorded as a binary number in an electronic counter.

4. Engineering Report No. 4:

Direct-Current Damping of a Two-Phase Servomotor

M. J. Fitzmorris
January 31, 1952

This report presents a study of the possibilities of using direct current in the field winding of a two-phase motor to increase the internal motor damping. A theoretical discussion of an elementary closed-loop system is used to illustrate the advantages to be obtained from increased motor damping. The actual performance of a typical two-phase instrument servomotor with direct current in one field winding is studied both theoretically and experimentally. Torque-speed curves for three values of direct current are presented and compared with the calculated curves.

The problems of magnetic saturation, heating, and the 60-cycle torque are discussed. The possibility of using the 60-cycle torque for either one in a hydraulic control system is presented.

The operation of a direct-current damped motor in a closed-loop system is investigated. The design of a power-amplifier stage to provide the direct current and of a mechanical damper to suppress the 60-cycle torque is discussed. The performance of the closed-loop system is studied in terms of its frequency response.

It is concluded that a definite improvement in the closed-loop system performance can be obtained by using direct-current damping. However, difficulties are encountered in the form of heating, saturation, low motor impedance, and the 60-cycle torque.

5. Engineering Report No. 5:

Investigation of a Servo-Type Pulse-to-Analog Data Converter

William L. Poland
November 27, 1951

This report describes the design, development, and testing of a closed-loop system, employing in the feedback path a quantizing element that converts electric pulses into the analog form of shaft positions.

A study of the effect of the quantizing element on the closed-loop behavior is reviewed. It leads to the conclusion that linear system-performance may be assumed for design purposes.

This report also includes a description of a method of algebraic

synthesis leading to the determination of the system parameters required to give the desired transient response of the closed-loop system. This method, embodying a restraint known as Krohn's criterion, leads to a means of relating the transient response and the frequency response of the closed-loop system. A series of non-dimensionalized curves that show this relation is contained in the report.

A breadboard model of the system is presented and tested in both the frequency and time domains. The results of these tests show that the assumptions made throughout the design are valid and that satisfactory system is realized.

6. Engineering Report No. 6: Tests on the Position Coder of a Numerically Controlled Milling Machine

J. H. Brown
April 21, 1953

This is a report of tests on an analog-to-digital converter, called the position coder, that is used in the decoding servomechanisms of a numerically controlled milling machine. The accuracy of the numerically controlled milling machine is dependent in part on the reliability of the position coder. The objects of the tests described in this report are to measure the reliability of this unit and to discover which part or parts of it are sources of any errors.

The investigation consists of operational tests of the position coder and tests of its components. Description and results of each test are given. Briefly, the result of the coder-drum test showed that when the .35-degree segment spacing was chosen, 15 synchronizing pulses per command pulse were required for satisfactory operation. As a result of the pickoff tests, it was found that intermittent failure could be attributed mainly to the ball-bearing pickoff, and that a glycerine and water solution, instead of oil, should be used to lubricate the bearings.

7. Engineering Report No. 7: Investigation of Methods of Data Preparation for a Numerically Controlled Planer

J. H. Runyon
June 1, 1953

This report describes a study made at the request of the Aero-

products Division of General Motors Corporation. An investigation was made of methods of deriving control information for a numerically controlled planer from data obtained from the present design process for airplane propeller-blade thrust members. In addition to discussions of procedures and costs of several different methods of data processing, there are included sample calculations, methods for determining the amount of data required, derivations of planer-tool center offset formulas, and a discussion of accuracies of the various methods of finding the desired data.

8. Engineering Report No. 8: Whirlwind I Routines for Computations for the M.I.T. Numerically Controlled Milling Machine

J. H. Runyon
December 1, 1953

Brief descriptions of Whirlwind I routines, useful in computations for the M.I.T. numerically controlled milling machine, are presented. These include:

- (1) Library subroutines written especially for milling-machine computations.
- (2) Library subroutines written by the Scientific and Engineering Computation Group of the Digital Computer Laboratory.
- (3) The Comprehensive System of subroutines, also prepared by the Scientific and Engineering Computation Group.

The descriptions are intended only to assist an analyst in selecting subroutines for a particular programming job.

9. Engineering Report No. 9: A Static-Magnetic Data-Storage Unit

R. H. Fuller
May 1, 1954

This report covers the design, construction, and evaluation of a data-storage unit proposed for use in an electronic, digital computer capable of controlling the metal-cutting operations of a machine tool. Command data are read from a punched paper tape and distributed into storage within a two-core per-digit magnetic shift register. Each digit in the command number thus stored is repeatedly and non-destructively interrogated through application of a pulsed, axial magnetic-field to the toroidal magnetic cores used to implement the shift register. Currents

necessary to generate the quadrature read-out fields are developed by a single electronic driver and routed to the required storage cores through selected, magnetic gates.

Systems of equations governing the operation of the magnetic shift and the operation of the magnetic gate are developed. Based on these two systems of equations, design procedures are developed for both the shift register and the magnetic gate. Experimental models of these devices are evaluated and operation correlated with that predicted from the above analyses.

Considerations involved in the design of necessary electronic circuits and output coupling circuits are presented. Operation of an experimental model incorporating these circuits with the magnetic-shift register and magnetic gate is then discussed. Special attention is given to the operating margins of the system and the degree of pre-selection of components necessary for proper system operation. An attempt is made to evaluate the expected reliability of the unit.

10. Engineering Report No. 10: Stabilization of Control System Having Coulomb Friction

John Steranka, Jr.
August 1, 1954

The subject of this report is the stabilization of a servomechanism having coulomb friction. This servomechanism, which is employed to drive a numerically controlled machine tool, exhibited small, sustained oscillations that contributed to undesirable waviness of the cutting surface.

The frequency-response method is employed by using the describing-function technique to represent the nonlinear effect afforded by the coulomb friction. The describing function is derived in a manner that deviates from the procedure presented in the literature. Rather than assuming a sinusoidal input to the nonlinearity, the writer considered the actual input waveform that was observed experimentally.

Stabilization is attained without altering the over-all system performance. It is accomplished by introducing an additional loop in the servomechanism that detects the positional input to the nonlinearity.

The system was redesigned and constructed employing the analytical technique above. Evaluation of the redesign showed that the small sus-

tained oscillations were eliminated.

11. Engineering Report No. 11: Theoretical Evaluation of the Accuracy of a Shaft-to-Phase Modulated Voltage Converter

J. H. Brown
September 1, 1954

This report describes a use of synchros or resolvers to convert shaft rotation to phase-modulated sinusoidal voltage. Conversion accuracy is analyzed by deriving equations which show the effect on the phase-modulated voltage of:

- (1) Unequal peak amplitudes of magnetic flux in the several stator windings.
- (2) Errors in the time-phase of flux in each stator winding.
- (3) Errors in the space-phase of the stator fluxes.
- (4) Harmonic fluxes.

One method of detecting the phase-modulated voltage is assumed, namely, time deviation of zero-crossings of the converter voltage from zero-crossings of a reference voltage. Error in the conversion of shaft motion to this time deviation of zero-crossings resulting from the above four causes is evaluated theoretically. For the special case of constant flux errors, reduction of conversion error is predicted through the use of an average phase of voltages induced in more than one rotor winding.

12. Engineering Report No. 12: A Single-Line Magnetic Shift Register Using Diode Amplifiers

Chris A. Lay, Jr.
May 23, 1955

This report covers the design, construction, and evaluation of a single-line magnetic-core stepping register using semiconductor-diode amplifiers. The pulse switching behavior of magnetic cores and the reverse-recovery characteristics of semiconductor diodes were investigated.

The single-line experimental stepping register will circulate a word at a 100-kilocycle rate with no deterioration in the switching behavior of the cores or diodes. The experimental register required half the input power and half the number of diodes and cores as compared to the standard

two-core per digit register used in most digital computers.

Two other circuits that make use of the hole-storage property of semi-conductor diodes are described. One results in non-destructive read out and the other, in word complementing. These circuits could save components in digital computer application and reduce input power requirements over the present circuits used.

13. Engineering Report No. 13: A System Study for a Digital-to-Analog Servomechanism

Theodore W. Tucker
December 27, 1955

A class of conditionally stable loop transfer-functions is analyzed and certain relationships are derived. An approximation method of analytically fixing the parameters of

$$KG = \frac{K(T_1 s + 1)^{(r - 1)}}{s^r (T_2 s + 1)^t}$$

is discussed. Nondimensionalized-transient-response curves are given.

14. Engineering Report No. 14: Numerical Control for Machining Warped Surfaces

George Bromfield
January 12, 1956

In order to produce warped surfaces, such as that of turbine-blade dies, on the M.I.T. numerically controlled milling machine, it is necessary to interpolate additional data on the given cross sections and additional cross sections between those given. It is then necessary to determine a set of points on a parallel surface one tool-radius away from the given surface corresponding to the interpolated network of points on the given surface. The resulting data must then be coded for the milling machine. In the case described in this report, all of the above steps were performed by the M.I.T. digital computer, Whirlwind I.

15. Engineering Report No. 15: Automatic Data Preparation for Numerically Controlled Machine Tools

J. H. Runyon
January 25, 1956

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A-30

This study is concerned with the use of Whirlwind I for the preparation of control data for the M. I. T. numerically controlled milling machine.

Digital-computer programming has been aided by the writing of 29 library subroutines. These subroutines perform commonly encountered steps in the preparation of control tapes for the M. I. T. milling machine.

The subroutines have been applied in routines for the preparation of control data for cylindrical surfaces (the boundaries of cams and templates), surfaces of revolution, and cones. From 75 to 90 percent of the Whirlwind I instructions in each of these routines has been obtained from library subroutines.

In addition to Whirlwind I, IBM equipment at M. I. T. and four other general-purpose computers operated by commercial computing services have been used to study tape preparation for the milling machine.

Suggestions for modifying the procedures for designing surfaces over which gas or liquid flow occurs have resulted from the study. These alterations would make desirable the use of general-purpose digital computers for engineering design and the eventual merging of control-data preparation with engineering design.

16. Engineering Report No. 16: Information Processing Routine for Numerical Control

Arnold Siegel
March 1, 1956

A fully automatic system has been developed for applying the Whirlwind I computer to the programming of the numerically controlled milling machine. The system is an experimental one, limited to figures composed of circles and straight lines, but the techniques are general and may readily be extended. The computer executes without human intervention all the computations needed to translate a simple description of the problem into a tape for the milling-machine control circuits. Since the user of the system employs only an easily learned "input language," he need not be familiar at all with the computer or its instruction code. Any errors in the input data are detected by the computer and are reported in the same simple language.

17. Engineering Report No. 17: Operations of a Numerically Controlled Milling Machine

D. C. Dick
March 15, 1956

During the machine-evaluation phase of the M. I. T. numerical-control project, 76 actual machine jobs were performed. The data available from each of the job records is summarized for most of these jobs which represent the extreme diversity of work which can be performed by the numerically controlled milling machine.

18. Engineering Report No. 18: Economic Studies of Work Performed on a Numerically Controlled Milling Machine

R. H. Gregory
T. V. Atwater, Jr.
March 1, 1956

During the three year-machine-evaluation phase of the M. I. T. numerically controlled milling-machine project, 76 different parts were studied. Estimates of small quantity manufacturing costs for ten of these parts were obtained from New England job shops. Comparison of these estimates is made with cost estimates based on actual man-hours expended by M. I. T. Servomechanisms Laboratory personnel. The comparisons show numerical control is now competitive with conventional manufacturing methods, but falls short of being an unqualified economic success principally because of high costs of programming.

19. Final Report Contract AF33(038)-24007 Design, Development and Evaluation of a Numerically Controlled Milling Machine

March 15, 1956

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CHAPTER IV

PROJECT FILES

A. GENERAL DESCRIPTION

In the development of the first practical general-purpose numerically controlled milling-machine system this project has gathered some files and records of potential historical or educational value. The following descriptions pertain to the extraordinary files, excluding the standard correspondence, purchase order, and work-order files and the files of regular reports described above.

B. MACHINE-TOOL JOB FILES

All documents associated with each job performed on the milling machine are filed in a job folder. The jobs are numbered in chronological order and indexed. Typical documents are part and fixture drawings, specifications, change orders, programming and computation sheets, program print-outs, and job analysis reports. The tapes are separately filed under the same job numbers.

C. PHOTOGRAPHIC FILES

Each of the jobs has been photographed - often as raw material, mounted on the machine, and as a completed piece. Many experimental setups and breadboards have been photographed. Prints and negatives of all photographs are filed in the project photograph file.

D. VISUAL AIDS

1. Slide File

Sixty black and white or color slides have been prepared for use in the many lectures, talks and classes presented by project members on numerical control. These are chiefly 3 1/4" x 4" standard glass slides, but a few 2" x 2" miniature color slides are included.

2. Motion Picture

A twenty-minute 16 mm sound motion picture has been made of the milling machine. Two copies of this film are available. The master copy is filed at the Worcester Film Corporation, Worcester, Massachusetts.

APPENDIX B

Part I of the first final report under Contract AF-33(038)-24007 was widely distributed (2,483 copies) but is still in demand. Since it has been out of print for some time, it has been included here for reference purposes.

As explained in the footnote on page 58, the number 6873-FR-1 has recently been assigned to this report for identification purposes.

Part II of the Final Report on Construction and Initial Operation of a Numerically Controlled Milling Machine, dated May 31, 1953, is not reproduced here. It is a complete technical description of the M. I. T. numerically controlled milling machine, and consists of seven chapters as follows: Introduction, Description of Operation, Personnel, Programming and Tape Preparation, Operating Instructions, Technical Description of Components, and Maintenance. There are three appendices: I-Tape Preparation Equipment, II-Tube Testing, and III-Engineering Drawings (bound separately).

A second printing (in 1955) of Part II has become exhausted and no copies are available at M. I. T. Appendix III is still available at a cost of \$55.00. To date, 30 copies of Appendix III have been purchased by companies and agencies interested in detailed information on the M. I. T. milling machine.

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22241

**Final Report on Construction
and Initial Operation of**

**A NUMERICALLY CONTROLLED
MILLING MACHINE**

Part I

July 30, 1952

This document reports the results of work made possible through the support extended the Massachusetts Institute of Technology, Servomechanisms Laboratory, by the United States Air Force, Air Materiel Command, under Contract No. AF33(038)-24007, M.I.T. Project No. D.I.C. 6873. It is published for technical information only and does not represent recommendations or conclusions of the sponsoring agency.

Approved: *J.O. McDonagh.*

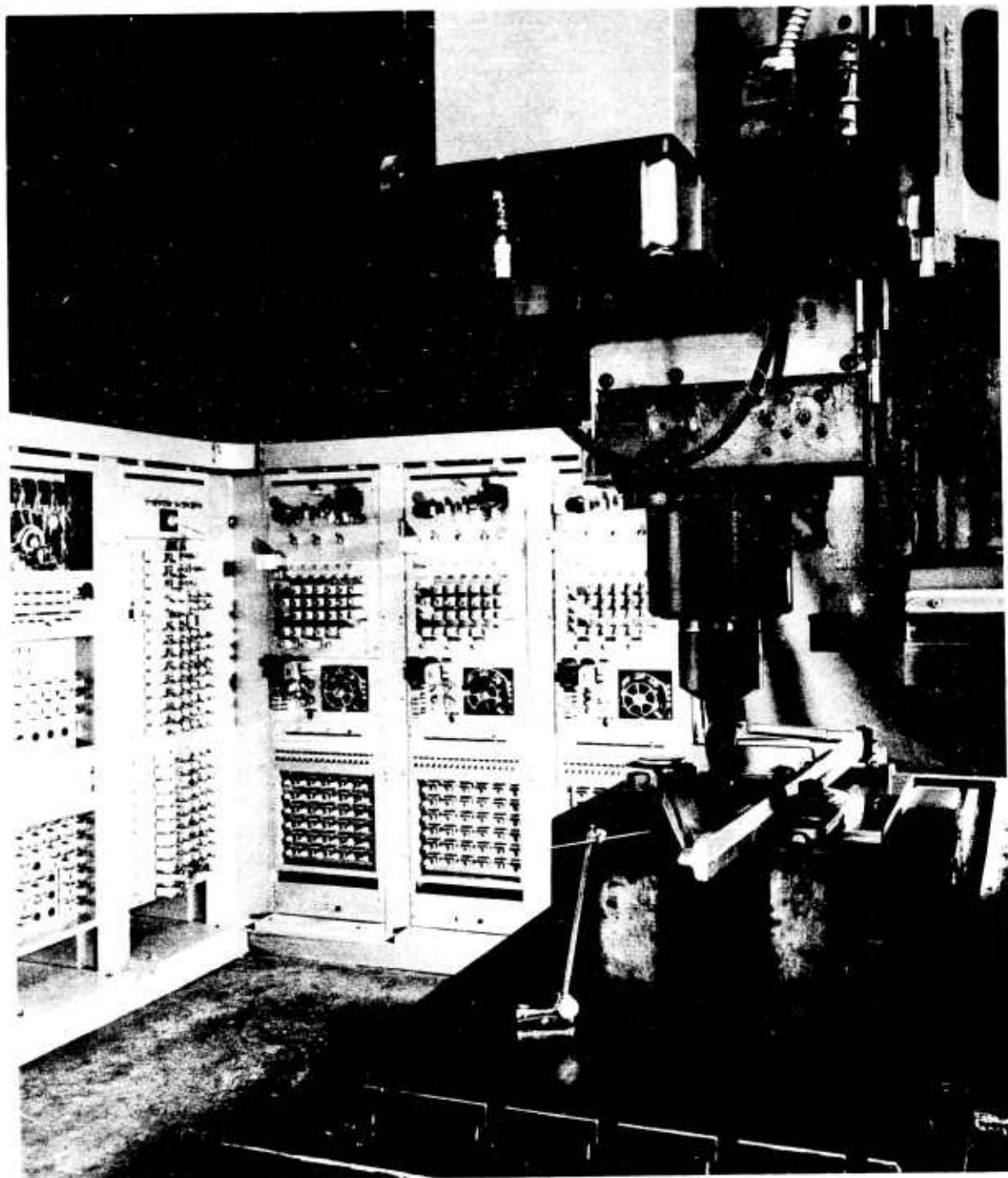
**SERVOMECHANISMS LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE 39, MASSACHUSETTS**

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ABSTRACT

Numerical control is a design technique which extends the benefits of automatization to moderate-volume manufacturing processes previously limited to manual production methods. A milling machine, now in operation at the Massachusetts Institute of Technology, illustrates the technical feasibility of numerical control and, on the basis of initial test operation, shows promise of becoming a valuable production tool.

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Frontispiece

PREFACE

For many years the Massachusetts Institute of Technology has been active in the development and exploitation of automatic control. A major advance in automatic control made possible by recent developments in the field of numerical information processing is the application of numerical techniques to the automatic control of such diverse processes as highway traffic, machine tools, chemical processes, steel mill operation, etc.

In a project utilizing this advance, the M.I.T. Servomechanisms Laboratory has developed during the past three years a numerically controlled milling machine. This project has included three phases:

1. A basic study of the principles of numerical control and its applicability to machine tools. This phase, sponsored by the Parsons Corporation of Traverse City, Michigan, under a contract with the U. S. Air Force, began in July, 1949, and ended in June, 1950.
2. The construction of an experimental milling machine controlled by numerical data on punched tape. This phase, sponsored first by the Parsons Corporation and subsequently directly by the U. S. Air Force, extended through March, 1952, when the machine was completed.
3. An analysis of the operation of the machine and an economic evaluation of numerical control. This phase, sponsored solely by the U. S. Air Force, began in February, 1952, and is scheduled to end in July, 1954.

The project was undertaken at M.I.T. in July, 1949, under the sponsorship of the Parsons Corporation which had secured a contract with the Air Materiel Command to design and build a milling machine to be directed by data punched on IBM cards. M.I.T. was requested to make a study of numerical control and to assist in the design of some components of the

machine. Initial exploratory work at M.I.T. disclosed a wide range of practical machine-tool systems. Of these, one which appeared most promising to both M.I.T. and the sponsor was chosen for detailed study. In June, 1950, the Servomechanisms Laboratory submitted a report covering complete performance and design specifications for this machine-control system.

A program to construct an experimental milling machine as outlined in that report was authorized by the Parsons Corporation and initiated soon thereafter. In setting up the program, which was wider in scope than that planned in 1949, it had become clear that the expenditure of time and money would exceed the initial Parsons Corporation estimates. In February, 1951, when construction of the machine was approximately 30 per cent complete, the Parsons Corporation terminated its sponsorship.*

Recognizing the potential value of the development of numerical control to the aircraft industry and encouraged by the progress in evidence at M.I.T., the Air Materiel Command decided to sponsor the continuance of the program under a contract between M.I.T. and the government. In March, 1952, construction of the machine system was completed.

Since the fall of 1951, the Laboratory has been engaged in a study of the application of numerical control to other machine tools and manufacturing processes of particular interest to the aircraft industry. Most promising among the applications under study are control systems for spar mills, boring mills, and drill presses.

This report is organized in two parts. Part I, intended for general distribution, contains a nontechnical description of numerical control and the machine at M.I.T. Part II, bound separately, gives a detailed technical description of the system and contains complete design information.

*The final report of the Parsons Corporation, entitled "Digitron," covers the work done at M.I.T. up to the time when the Parsons Corporation withdrew from the program.

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SUMMARY

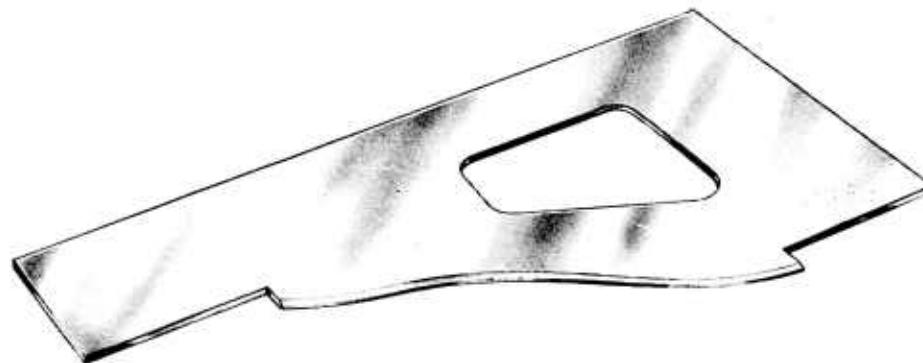
A new technique of automatic machine-tool control now being demonstrated at the Servomechanisms Laboratory at M.I.T. promises to simplify some of the manufacturing problems of medium and small run production often encountered in the aircraft industry.

Called numerical control, this technique has been applied by M.I.T., under the sponsorship of the Air Materiel Command of the U. S. Air Force, to a milling machine controlled by a numerical code punched on paper tape.

Since March, 1952, when construction was completed, the milling machine has been used as an experimental production unit to evaluate the economic aspects of numerical control* and as a basis of a study of the application of numerical control to other machine tools and manufacturing processes of particular interest to the aircraft industry.

While a complete evaluation will be possible only after the present program of trial operation has been carried much further, it is already clear that the numerically controlled milling machine is a valuable production tool which combines high productivity, flexibility, and precision. The control system, during approximately 4,000 hours of operation, has exhibited a high degree of reliability. Operational experience shows that the system requires as little maintenance as the basic machine tool.

*See Appendix for examples of typical work pieces made.

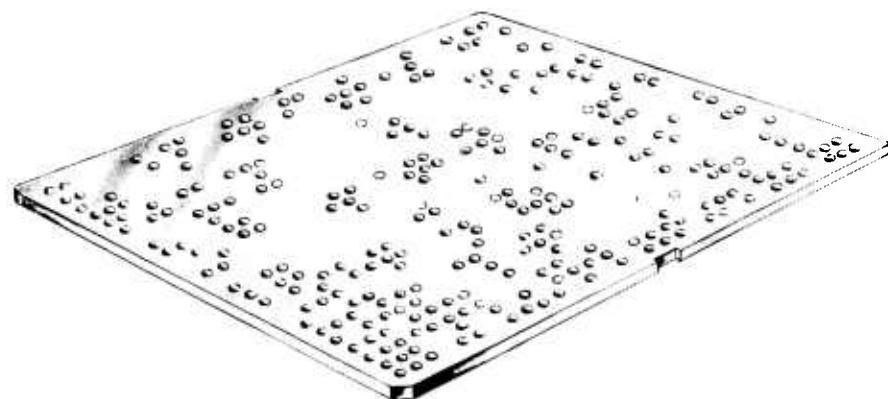


CONVENTIONAL AUTOMATIC CONTROL

In the past, various types of production tools have been designed which can automatically execute complete machining operations under the control of built-in devices such as cams, templates, masters, limit stops, etc. The fabrication and setup of such control devices are elaborate, time-consuming, and costly. These costs can be absorbed readily if large quantities of the same part are to be made, but cannot be justified in short-run production.

For some applications, it has been possible to achieve reasonably simple setup and control equipment, but only by reducing machine flexibility, i.e., the variety of operations which can be performed on a given machine. Here again, short-run production industries are at a disadvantage, for they have little use for special-purpose machinery.

Thus, the short-run production industries, in particular the aircraft industry, need automatic machinery whose flexibility is not limited by control equipment and for which entire setups may be prearranged in a form that can be slipped into the machine in negligible time.



NUMERICAL CONTROL

Numerical control in its application to machine tools means that the tool is guided over the work without human intervention in response to a series of instructions previously recorded in a numerical code on such media as cards, paper tape, magnetic tape, or film. In the M.I.T. application, patterns of holes punched on paper tape represent the dimensions of the work piece and other specifications of the machining process.

Numerical control offers all the benefits of automatic operation together with certain advantages not realized through the use of conventional control techniques. Most prominent among the additional advantages of numerical control are:

1. All the machining operations which lie within the capability of the basic machine tool can be performed automatically.
2. The control equipment can be changed from one job to another in negligible time by simply inserting a new set of previously prepared instructions.
3. For a given job, the number of work setups as well as the time spent on each setup are reduced.
4. Control instructions can always be made as accurate as desired.
5. A single control system is capable of directing more than one machine and need not be located near the machine tool.
6. The instructions do not deteriorate with use, are readily modified through patching techniques, can be stored conveniently, shipped anywhere with economy and speed, and transmitted between factory installations by means of conventional teletype circuits.
7. Nearly all of the components in a numerical control system are of commercial grade, readily available at moderate cost.

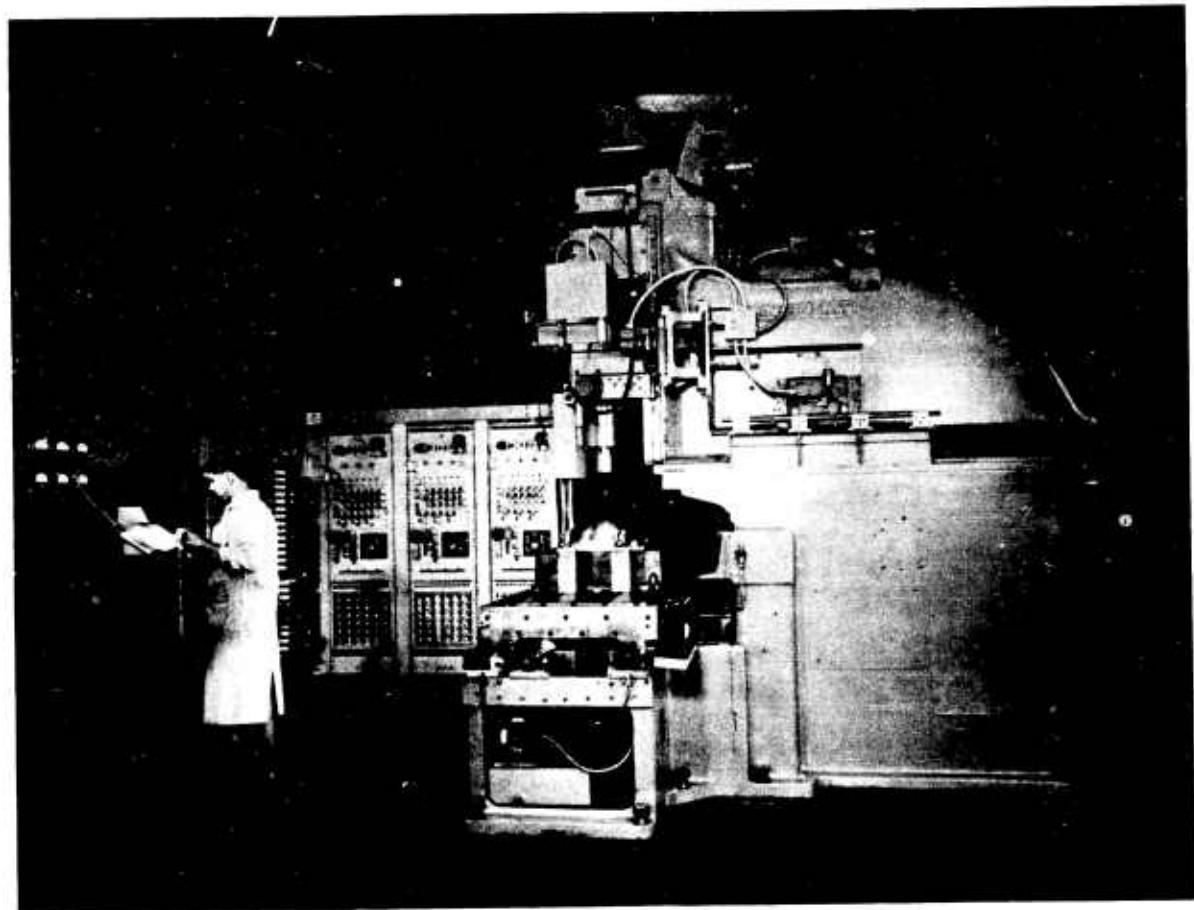


Fig. 1 General View

THE M.I.T. NUMERICALLY CONTROLLED MILLING MACHINE

Description

The components of the system now in operation at the Massachusetts Institute of Technology have been grouped into two major assemblies. The milling machine and the equipment needed to control its several motions form a unit here called the "machine," while the data-handling equipment forms a separate unit called the "director."

Part II of this report, separately bound, contains a detailed technical description of the M.I.T. machine and complete design information.

A functional description of the present system is given in a brochure for general distribution entitled "A Numerically Controlled Milling Machine," published by M.I.T. in October, 1951.

A view of the numerically controlled milling machine is shown in Figure 1. The basic machine tool is a government-furnished Cincinnati Hydro-Tel, with all of the original drive and control equipment replaced by equipment designed and built by the Servomechanisms Laboratory. The machine now has a work capacity of 60 x 30 x 14 inches. All three of its motions (table, head, and cross-slide) have been provided with numerical control so as to allow any combination of the three motions to take place in synchronism. Hence, the tool can now be guided over the work along any desired path.

The director is shown at the left in Figure 1. Since the initial system was required to lend itself readily to design modifications, the physical layout of the director was determined largely on the basis of convenient accessibility of parts, rather than minimum size. Similar units for commercial use will be packaged in a more compact form, and it is expected that future models of similar equipment will occupy approximately 12 square feet of floor space.

Applicability

The M.I.T. numerically controlled milling machine can be used to make a variety of parts lying in many separate design areas. Examples of its work include die sinking, template making, manufacturing of large

structural parts of air-frames, finishing of forgings, contouring of complex three-dimensional parts, finishing of castings, jig boring, etc. Three typical pieces produced under numerical control are described in the appendix of this report.

The present controls can direct more than one milling machine or any number of other machine tools. It is not necessary that the control equipment be located near the machine tool, and future applications may involve a single controller guiding machines in separate factory installations.

Reliability

Work spoilage due to machine failure has been negligible and experience gained in the first 4,000 hours of operation indicates that the control equipment requires no more maintenance than the basic machine structure.

Operation

The machining of a part on the numerically controlled milling machine is guided by a series of instructions that take the form of patterns of holes punched on paper tape. The length of the tape varies with the job. A single machine instruction is sufficient to guide the tool over the work along a straight line regardless of its length. One pattern of holes occupying an inch or two of tape specifies the direction, the speed, and the distance that the tool is to move. A new instruction, having a different code pattern, is supplied by the tape each time the cutting tool changes direction in passing over the work.

In this system, it is possible to cut any curved surface by approximating it with straight lines. For example, a circle is approximated by a polygon. The number of sides in the polygon will then determine how closely the result approximates a circle, and how long the tape will be. It is always possible to make the curve as smooth and accurate as the cutting characteristics of the machine permit. Any measurable deviation of the work from the desired curve results from tool marks and other residual machining uncertainties.

TAPE PREPARATION

The steps in the preparation of the instructions for the M.I.T. machine include determination of the desired tool path over the work, reduction of that path to incremental straight-line segments, numerical specification of the end points of the segments, translation of the specification into a form which can be punched on paper tape, and perforation of the tape.

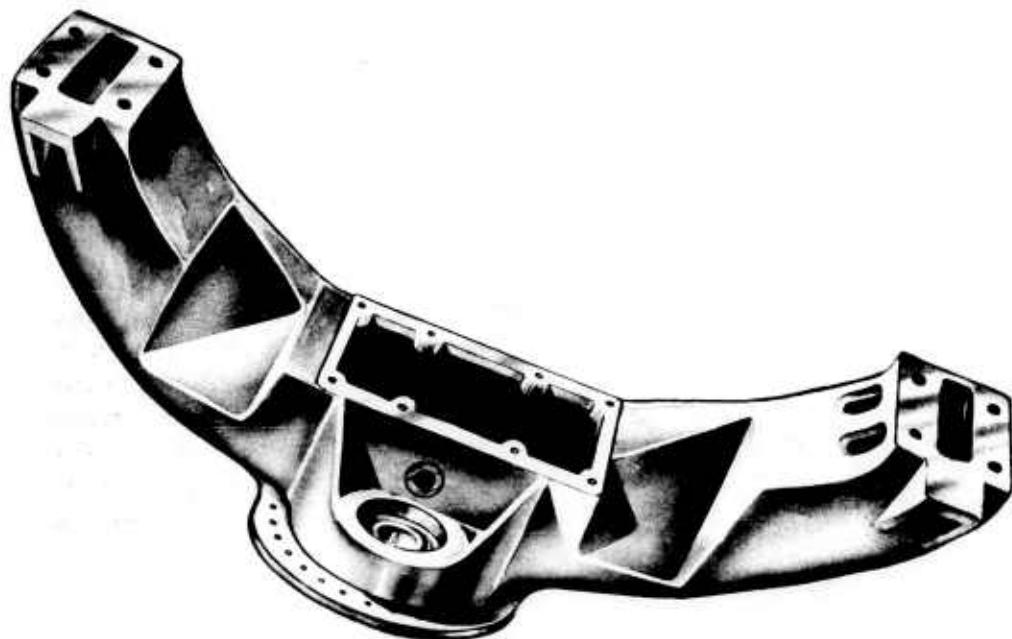
In more detail, the programming procedure is as follows. On the basis of the drawings and specifications of the part to be machined, the desired cutting paths and feed speeds to be used in machining the work are determined. Since this determination involves the conventional decisions as to cutter type, dimensions, and performance, sequence of machining operations, setup of work on the machine, etc., it requires a sound knowledge of machining practices.

The locus of the tool center which will produce the desired cutting paths is next determined by making proper allowance for the geometry of the tool. This locus is then divided into a series of straight-line segments. The segments should be as long as possible without differing from the desired tool-center locus by more than the machining tolerance. Each straight-line segment requires a separate instruction. Hence, the longer the segments, the smaller the number of instructions. As the segments need not be parallel to the machine ways, their dimensions must be resolved into components parallel to each of the three orthogonal motions of the machine. The time to be consumed in executing each straight-line segment at the desired feed rate is then specified. The above steps vary in difficulty of computation with the particular part to be made. They can be reduced to routine computations for many useful types of work.

Next, the three components and the time interval for each segment are tabulated in a predetermined order to form a single set of control instructions for which there will be a unique pattern of holes, one to two inches long on the tape. Instructions for all of the segments are similarly tabulated in the order in which they will be used by the machine. The tabulated sets of instructions are transferred to paper tape by a copying operation in which the tabular data are retyped, using a special keyboard

electrically connected to a tape punch. The equipment automatically punches the proper pattern of holes on the tape as each key is struck. The tabulation and copying are simple clerical operations.

In preparing the tapes, the programmer is required to have a thorough knowledge of the machine characteristics, metal-cutting practices, geometry, and trigonometry. He will generally find it convenient to make use of a desk calculator in order to reduce the amount of routine arithmetic. The entire programming procedure, while frequently lengthy, is rarely difficult and requires a degree of skill no greater than that presently available in such personnel as junior engineers, design draftsmen, or members of a computing section. For some work pieces, the instructions may be prepared more efficiently through the use of machine-computation techniques, in which case tape can be automatically prepared by modern digital computers such as the IBM equipment now available in many industrial establishments. A number of automatically prepared tapes have been used at M.I.T.



DESIGN OF NUMERICAL CONTROL SYSTEMS

System Study

In developing a numerical control system for a particular application, the designer must perform first an over-all study in which he takes into account the degree of automaticity required, the type of machining operation to be performed, and the general form of the equipment to be used in the system. The results of this study will specify a system which may range in complexity from a simple ratchet-type drive to a complex equation-solving system.

In general, there is an inverse relationship between the length of the instructions necessary to machine a given part and the complexity of the electrical system necessary to execute these instructions. But while a complex control system is necessarily high-priced, the initial cost may, in many applications, be more than made up during operation by the savings resulting when only brief instructions need to be prepared for the machining of a part.

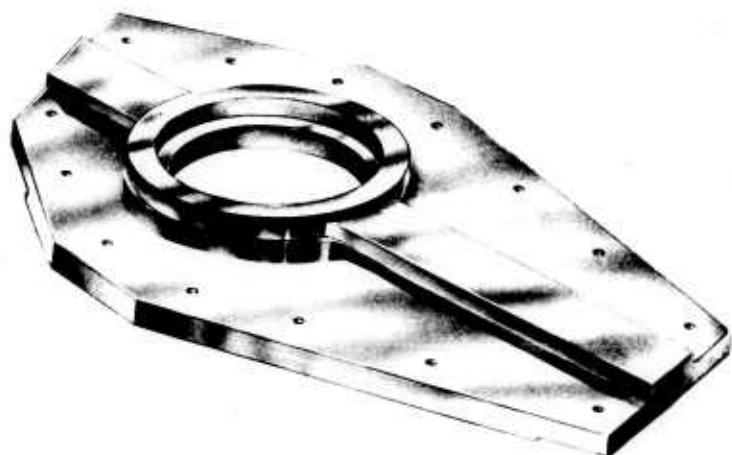
Design Execution

Considerable technical latitude is left to the designer. For some applications, he may find it best to use a system where complete machining processes are built up out of combinations of as few as three basic instructions: move forward a unit step, move backward a unit step, and stand still. The size of the unit step may be whatever the specification for the smallest machine motion is, for example, 0.001 inch. Consider a table-positioning machine for which numerical control of this type is to be provided on two motions, called "x" and "y," at right angles to each other. Any point on the table can then be located by moving in the x and y directions a number of steps equal to the number of thousandths of an inch contained in the desired motions. If a typical part requires x-motion of 5 inches and y-motion of 4 inches, both forward, there must be a sequence of 5,000 "move forward" code numbers for x and 4,000 "move forward" code numbers for y. A very long control tape then results. However, while the preparation of such a tape is tedious and time-consuming, the resulting system may use control apparatus which is very simple, taking the form of elementary

ratchet-type drives. The above example illustrates lengthy instructions but simple and therefore low-cost equipment.

Other applications may dictate the use of a design scheme resulting in brief instructions and complex control apparatus. For such work as airfoils, characterized by an equation containing but a few constants, it may be best to design a control system capable of solving the equation by which the work surface is described and of guiding the tool over the work so as to generate the desired surface. The instructions then need to be only the constants in the equations and are, therefore, very brief. However, the required computational equipment and control system will be complex and, hence, high-priced.

The two examples cited above illustrate the end points of a wide range of design possibilities and the inverse relationship between the length of the instructions necessary to machine a given part and the complexity of the electrical system necessary to execute these instructions. The design of the present M.I.T. machine falls somewhere between the extreme possibilities. Future applications of numerical control may require designs which tend to lie nearer one of the extremes.



FUTURE PROGRAM

The present phase of the M.I.T. project began in February, 1952, and is scheduled to end in July, 1954. This phase, sponsored by the U. S. Air Force, includes investigations in three general areas:

1. **System Studies.** The investigation of typical industrial problems, work programming, and new machine-tool systems, with a view toward optimizing the over-all production processes studied through the application of modern information and work-processing equipment. This study will concentrate on determining the most desirable type of machine for a given process and the optimum methods of designing, planning, and computing work for numerically controlled production. It will culminate in the specification of the logic and block diagrams for one or more prototype machines.
2. **Machine Operations.** The investigation of the characteristics of numerically controlled machine tools through the use of the present machine on pilot manufacturing tasks. The economics of numerical control as affected by the costs of programming, computation, maintenance, and operation are being studied by an operating group organized to do productive work on the manufacturing of aircraft parts and other similar problems.
3. **Component Studies.** The investigation of circuits, circuit components, measuring devices, and other subsystems to insure that future numerically controlled machines may make maximum use of current technology. These studies are directed toward improvements in reliability, accuracy, and speed of numerically controlled machines by improvements in the components and subsystems. Vacuum-tube replacements, counters, optical measuring devices, information-input media, reading equipment, and antifriction linear bearings are examples of the areas in which experimental work is planned.

APPENDIX

TYPICAL MILLING-MACHINE WORK PIECES

This section describes three typical machining jobs that have been performed by the numerically controlled milling machine. These examples were chosen because they illustrate several different areas in which numerical control may show advantages. The first, "Cam No. 2," illustrates the flexibility of the numerically controlled machine in producing work which requires boring and contouring, both along straight sections and curves, and plain milling. In addition, the preparation of tape for Cam No. 2 illustrates all of the steps involved in programming a numerically controlled machine tool. The second example, "Luneberg Lens," illustrates the application of the numerically controlled milling machine to a job in which accuracy in contouring a sculptured surface is the prime requirement. The third example, "Forward Drag Strut," illustrates the application of numerical control to the automatization of a series of plain milling operations.

1. Cam No. 2

Cam No. 2, shown in Fig. 2, is a demonstration piece milled from aluminum stock, $1/2$ inch thick. It illustrates the ability of the machine to make automatically a sequence of cuts in various directions and the practicability of approximating curves by a series of straight-line cuts. The left-hand quadrant of the semicircle at the top of the cam is composed of chords of 5° arcs, which differ from a true circle by no more than 0.004 inch. The other 90° of the semicircle are composed of chords of 1° arcs, resulting

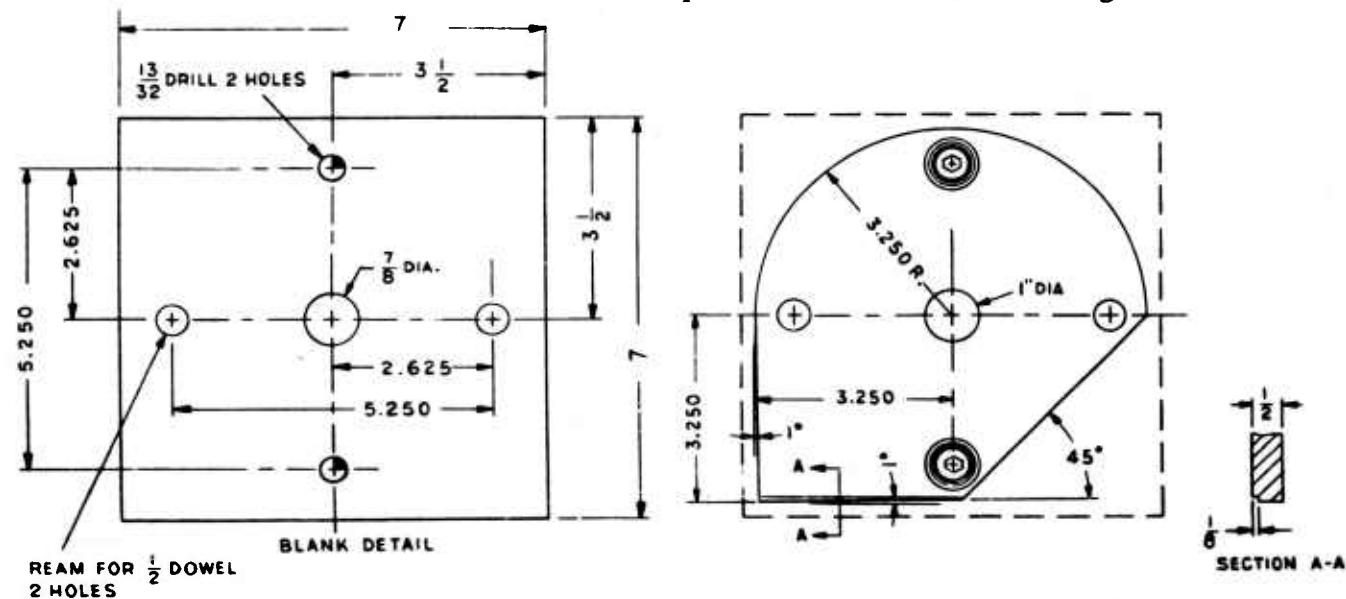


Fig. 2 Cam No. 2

in a surface whose only measurable deviation from the desired circular arc is that due to tool marks and machine vibrations. The machine orders for these arcs were computed and punched on paper tape by an automatic digital computer. The sides forming the 90° angle at the left-hand corner and the 135° angle at the lower edge of the cam are rotated 1° with respect to the corresponding machine axes. This skewness is emphasized in the part by taking a shallow cut parallel to the x-axis at the bottom edge of the cam.

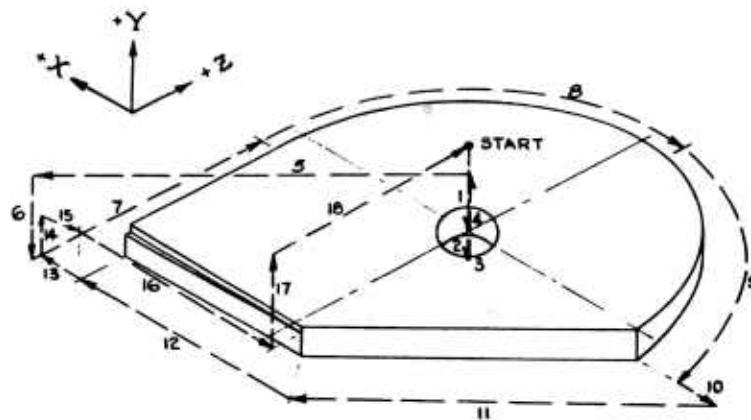


Fig. 3 Sequence of Machining Operations on Cam No. 2

The first step in the preparation of the instructions was the specification of the sequence of machine operations listed below. The item numbers refer to the arrows in Fig. 3 which indicate the paths of the tool center.

1. From a point one inch above the reference point on the blank, move downward .875" at 15" per minute, the maximum rate of tool movement.
2. Plunge into blank at 5" per minute for .6875".
3. Stop for 2 seconds.
4. Raise tool 1.0235" at 15" per minute.

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5. At 15" per minute, move to directly above the cutter center at the beginning of the first cut on the outline of the cam.
6. Move tool downward 1.0235" at 15" per minute.
7. Cut straight side at 15" per minute.
8. Cut first 90° of 5° increment circle.
(Insert blocks from previously prepared tape.)
9. Cut second 90° of 1° increment circle.
(Insert blocks from previously prepared tape.)
10. Move to start of 45° straight cut.
11. Make 45° cut at 10" per minute.
12. Perform straight cut at 15" per minute.
13. Move tool .25" away from work.
14. Raise tool .4375" at 15" per minute.
15. Return tool to work and in addition cut into work for .0355" along z-axis.
16. Move 3.5" along x-axis at 15" per minute.
17. Raise tool 1.25" at 15" per minute.
18. Return to starting point.

Pauses are inserted throughout the program where desirable to prevent the tool from overshooting. The tape for the linear portions of the cam was prepared manually and combined with the automatically prepared tapes for the circular arcs. A one-inch diameter, two-fluted end mill is used for all cuts.

The time required for computing the manually prepared part of the tape, punching, proofreading, and correcting the tape, and combining the manually and automatically prepared parts was four man hours. The resulting tape is 172 inches long and serves for both right-handed and left-handed parts. The machining time per piece is 5 minutes on the numerically controlled machine as compared to approximately four hours on conventional milling machines. To date, approximately 20 cams, produced in several different runs, have demonstrated the reproducibility made possible by numerical control.

2. Luneberg Lens

At the request of the Air Force Cambridge Research Center, the numerically controlled milling machine was used to machine the male section of a Luneberg Lens. A picture of the finished piece is given in Fig. 4. At its widest diameter the part measures 15.960 inches and the over-all height is 4.755 inches. The lens was machined out of a fabricated blank, part of which was magnesium and part aluminum.

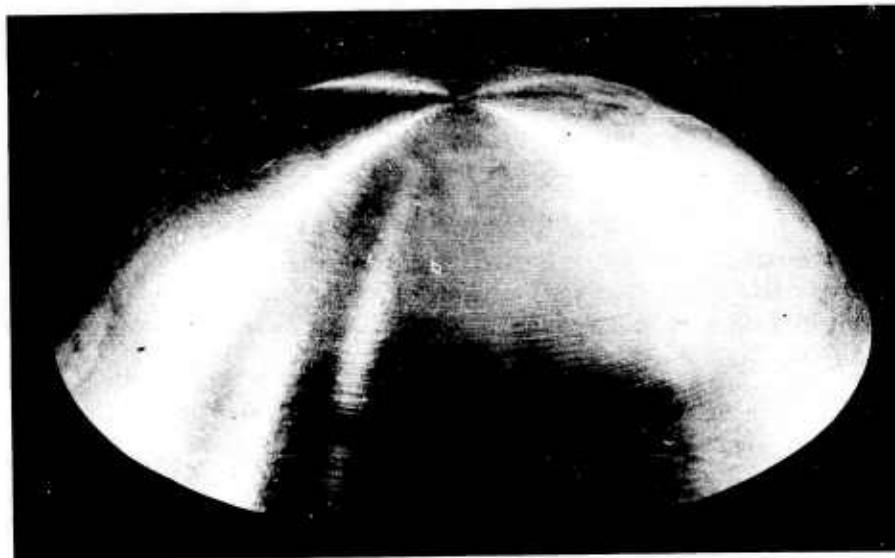


Fig. 4 Luneberg Lens

The machining consisted of the radial contouring of a mathematically defined surface to within minus 0.000, plus 0.001 inch. The necessary machine instructions consisted of 71 sets of dimension points in the vertical and radial distance, which, when coded, occupied 130 inches of tape. All of the computations were carried out by the Cambridge Research Center which supplied the data to M.I.T. in the form of a table, properly corrected for the geometry of the two-inch diameter ball-end mill used for cutting.

Prior to the final cutting operation, four roughing cuts were taken, also under numerical control. Since the work piece has cylindrical symmetry, it was most expedient to mount the work on a rotary work table which, in turn, was mounted on the table of the numerically controlled milling machine. Thus, only two machine motions were under tape control: the machine head and the machine cross-slide.

In order to avoid exceeding the limited capacity of the only rotary work table immediately available, it was necessary to program this work so that each pass of the tool over the work took more than two hours. The time summary for the entire manufacturing process is as follows:

| | |
|--------------------|-------------|
| Tape preparation | 6 hours |
| Setup of work | 2 hours |
| Roughing operation | 9 hours |
| Final cut | 2 1/2 hours |

Comparison between the performance of the numerically controlled milling machine and that of conventional machinery would be unrealistic in this case since numerical control is presently the only known method of producing a part of this nature to a known accuracy all over the surface.

3. Forward Drag Strut

One of the areas in which the numerically controlled milling machine is expected to be particularly useful lies in the finishing of press forgings of aircraft parts. To explore this field of work, the machine has been used to finish the forging of Boeing Airplane Company Part No. 5-30384-2, Wyman-Gordon identification number 20059A. The forging, as received by the Servomechanisms Laboratory, is shown in Fig. 5. The milling operations carried out are shown in Fig. 6. In addition, to these operations, drilling, boring, spot facing, minor hand fairing, chamfering, and finishing remains to be done on the piece as presently performed after it leaves the numerically controlled milling machine. The instructions are written so that they may be executed in two setups, as shown on the drawing. Three end mills having diameters of 1.75, 1.5, and 0.5 inches are used. All major cuts are programmed for both a rough cut and a finish cut, but, in general, the finish cut is made immediately after the rough cut.

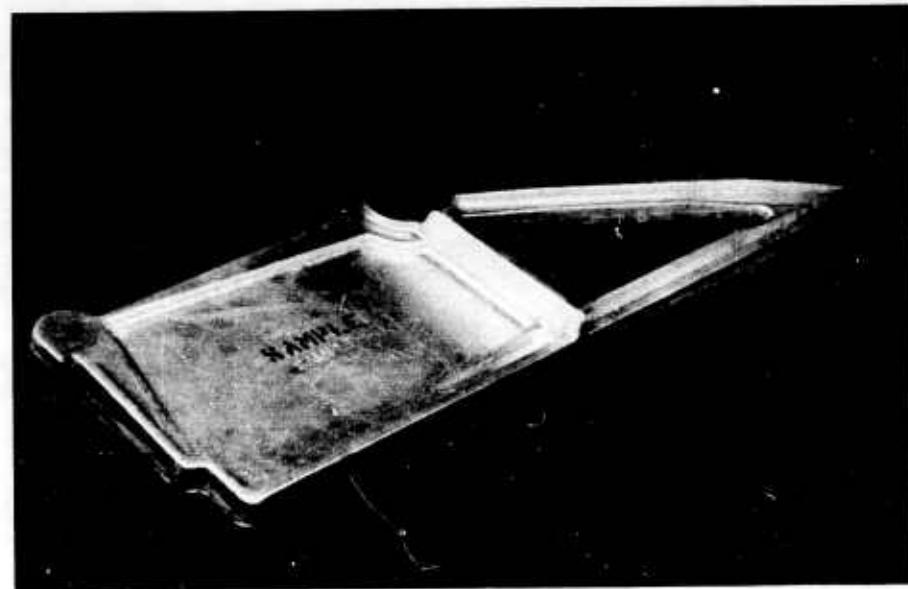


Fig. 5 Drag Strut Forging

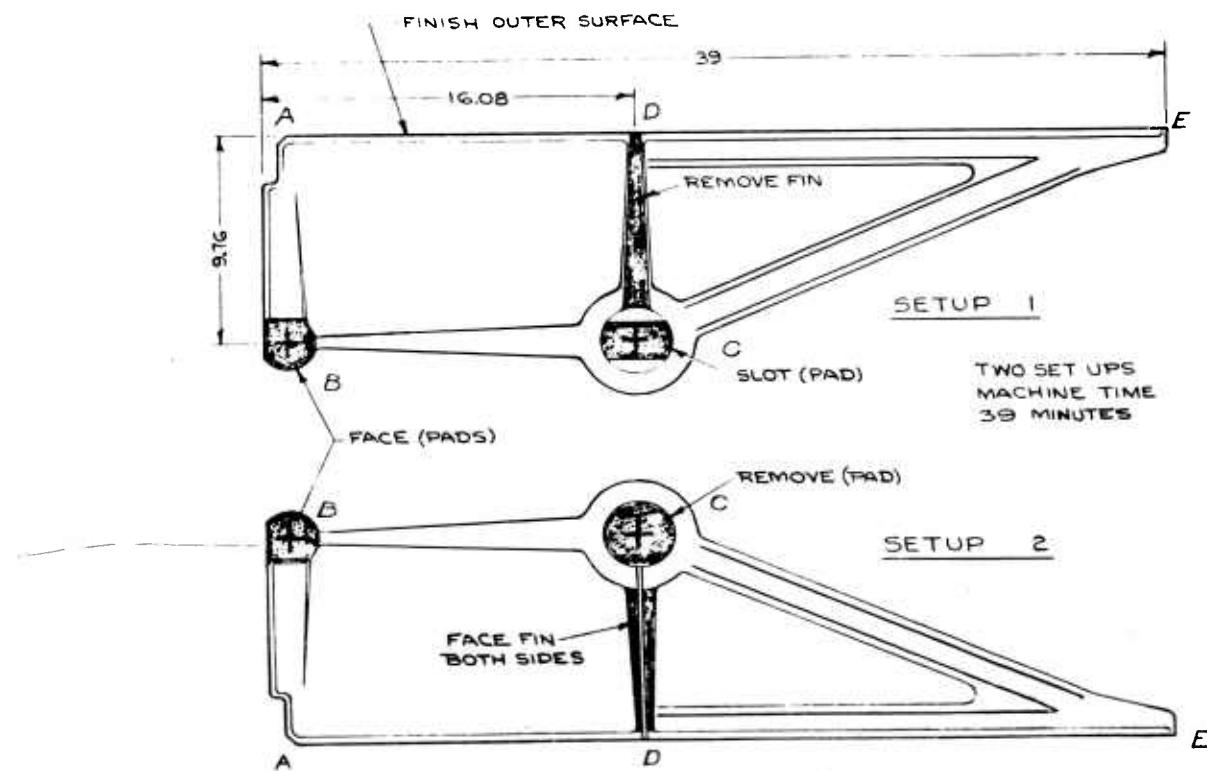


Fig. 6 Machine Operations on Forward Drag Strut

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Using the 1.5 inch diameter tool, the sequence of operations on the first setup, illustrated at the top of the drawing, is as follows:

1. Remove fin CD.
2. Slot pad C.
3. Move to position above pad B.
4. Stop.
5. Manually lower tool half the original thickness of C.
6. Face pad B.

On the second setup, the sequence of operations is as follows, starting with the 1.75 inch diameter tool:

1. Rough cut fin CD and pad C.
2. Finish fin CD and pad C.
3. Clean up 0.38" fillet on end of fin at C.
4. Face pad B.
5. Machine outside surfaces BA and AE.
6. Move to A.
7. Stop.
8. Change to 0.5" diameter end mill.
9. Mill fillet and chamfer at A.

The following summary lists the pertinent time records:

| | |
|--|------------|
| Tape preparation | 16 hours |
| Work setup (special fixtures used) | 2 hours |
| Automatic milling operation | 24 minutes |
| Manual intervention during milling operation | 15 minutes |

A time record for the same operations presently carried out by conventional methods lists the following items, as submitted by the Boeing Airplane Company:

| | |
|-------------------|-------------|
| Setup | 27 hours |
| Milling operation | 169 minutes |

The large reduction of setup time for the numerically controlled milling machine as compared to present methods results from a reduction of the number of setups. While the numerically controlled milling machine requires only two setups, nine setups are required for conventional methods, involving two separate machines, a Cincinnati Hydro-Tel (in this case used only as a plain milling machine) and a No. 4 Milwaukee plain milling machine.

Left-handed parts will also be made from the same forging, in which case the slot in pad C will be omitted. It is estimated that the preparation of the tape for the left-handed part will require approximately one hour. In the general case where left- and right-handed parts differ only in a rotation of axes, the numerically controlled milling machine can make both parts from the same tape. Only a manual switching operation requiring negligible time needs to be done to obtain either part.

APPENDIX C

APT Press Conference

February 25, 1959

1. PURPOSE

As the date approached for actual use of the Industrial APT II System in the aircraft industry, the three groups involved in its development each felt that there should be a suitable formal public announcement. APT represented a substantial effort in time and money on the part of all concerned and a well-timed formal announcement appeared to be an important element in the APT development program, both to stimulate interest in APT on the part of the public and potential users, and as recognition of the work accomplished. Accordingly, plans were made during 1958 for a joint MIT-AMC-AIA Press Conference in early 1959, and it was decided that M. I. T. was the best place to hold it. The conference resulted in widespread publicity in newspapers, trade journals, general news magazines, and radio-TV, and the large number of information requests received as a result indicated successful dissemination of the APT story.

This appendix presents data relative to the purpose of the Press Conference, the speakers and program, and a list of attendees from the press and industry.

2. INVITATION TO THE PRESS

Shown on the next page is a copy of the general announcement and invitation, which was sent to about 100 news media and science writers.

3. PRESS KIT

Upon arrival at the conference, each attendee was given a press kit containing the following:

- a. What is the APT System
- b. How the APT System Works
- c. Explanation of APT System for Technical Press

Office of Public Relations

February 5, 1959

To the News ~~Editor~~:

You are invited to attend a press conference on the APT System to be held at M.I.T. from 9:30 a.m. until approximately 3:30 p.m. on Wednesday, February 25, to see a demonstration of a new system for automatically programming machine tools.

"APT" means Automatically Programmed Tools. The system is expected to result in savings of millions of dollars to the aircraft industry in coming years. It marks the "marriage" of digital computers and numerically controlled tools so that scientific methods can be applied to engineering and production methods.

The APT system was developed during the past two years through an unusual cooperative venture involving research by the M.I.T. Servomechanisms Laboratory and field trial work by some 20 leading American aircraft plants. The system has the potential for being a major factor in the nation's industrial economy.

Working in cooperation with the Aircraft Industries Association and the Air Materiel Command, United States Air Force, we have prepared releases, pictures and other material on the system. This will be available in press kits at the conference, and advance releases will be mailed to you later this month. Representatives of all three agencies will present the background, history, technical details and potential of the system. A demonstration will be held at the M.I.T. Computation Center and at the Servomechanisms Laboratory. There will be a period for questions and discussion.

Cameras, both still and motion picture, will be welcome. All media representatives are invited to be our guests for cocktails and luncheon in the Campus Room of the Graduate House on the M.I.T. campus. We have been fortunate in obtaining as a luncheon speaker Lt. General C. S. Irvine, Deputy Chief of Staff for Materiel, Hq. United States Air Force. Following the luncheon, another discussion of the APT System will be held for those who wish to remain for additional technical details.

You are asked to meet in the Little Theater of Kresge Auditorium on the West Campus, directly opposite the main entrance to M.I.T. on Massachusetts Avenue. We would appreciate all media representatives being present by 9:15 a.m. Would you please return the enclosed card with the names of those planning to attend the conference so that we may receive it not later than Friday, February 20?

Sincerely,

Francis E. Wylie
Director of Public Relations

- d. Diagrams of how APT System is Used
- e. Major Dates on Numerical Control and APT System Development
- f. News Release - AMC - Information Office
- g. Brief Biographies - MIT Personnel responsible for research efforts
- h. Biographical Sketch - J. A. Maurice
W. M. Webster
Lt. Gen. Irvine
- i. History of the Servomechanisms Laboratory
- j. ASME Publications - papers by D. T. Ross
W. M. Webster
Wm. Beeby
- k. Pictures of Ross, Irvine, Perry
- l. Pictures of Machine Tools (Nine)
- m. A souvenir ashtray programmed with APT and machined on the MIT numerically controlled machine tool. (See photo on page 21)

4. RESUME OF PROGRAM

- 9:30 - 9:35 Welcome and opening remarks by Dr. Gordon S. Brown, head of the Department of Electrical Engineering, M. I. T.
- 9:35 - 10:40 Technical Session with talks by:
J. A. Maurice - Aircraft Industries Association
W. M. Webster - Air Material Command, USAF
D. T. Ross - Servomechanisms Laboratory, M. I. T. (detailed explanation of APT)
- 10:45 - 12:00 Demonstrations of APT on the IBM 704 Computer at the M. I. T. Computation Center, and of numerically controlled machining at the Servomechanisms Laboratory.
- 12:05 - 12:30 Question period with panel of M. I. T., AMC, and AIA speakers, moderated by Prof. J. F. Reintjes.
- 12:30 - 2:30 Luncheon meeting, with address by Lt. General C. S. Irvine.
- 2:30 - 3:30 Final question period.

5. LIST OF CONFERENCE ATTENDEES

| | |
|----------------------|--|
| Ben Lee | Assist. Direc. Public Relations, AIA |
| James J. Haggerty | Missiles and Rockets Magazine |
| Robert Loebelson | Space Aeronautics |
| Allen M. Smythe | Magazine of Wall Street |
| Henry T. Simmons | Newsweek |
| Raymond H. Spiotta | Associate Editor, Machinery |
| Larry Tully | Aviation Week |
| Sam Cummins | Automotive Industry |
| R. W. Bolz | Editor, Automation |
| Byron K. Ledgerwood | Managing Editor, Control Engineering |
| William M. Stocker | American Machinist |
| Robert Whitlock | Electrical Engineering |
| Benedict Learburger | Product Engineering |
| Peter Kaprillyan | Technical Editor, Aircraft and Missiles |
| John R. Riggs | Associate Editor, Electrical Manufacturing |
| Harry Samuels | Popular Science |
| Glen Nixon | U. S. News and World Report |
| Edward J. Egan, Jr. | Iron Age |
| Cal Campbell | Boston Herald, Popular Mechanics |
| Juan Cameron | Boston Herald |
| Reporter | Boston Daily Record |
| Tom Maguire | Electronics |
| Reporter | Boston Herald |
| Reporter | Boston Globe |
| Dave Muggeridge | Electronic News |
| Howard Rains | Electronic News |
| Alan Mayers | WGBH/FM |
| Barry Roach | The Tech |
| Jim Kistler | The Tech |
| Volta Torrey | Tech Review |
| Ruth Mehrtens | Time |
| David Wurzel | UPI Photos |
| Ed Fitzgerald | UPI Photos |
| Richard Growald | UPI Newsdesk |
| Brenton Willing, Jr. | Business Week |
| Loren Bullock | IBM |
| J. M. Wicker | IBM |
| J. P. Rankin | Convair, Fort Worth |
| Theodore Merrill | Business Week |
| Ralph Morse | WEEI(CBS) |
| Frank Prendergase | Industry |
| Albert Hughes | Christian Science Monitor |
| Photographer | Boston Globe |
| Harry Wharen | Metalworking |
| Roger May | Worcester Telegram |
| Arthur Gaskill | Movietone News |
| Wallace Dickson | Federal Reserve Bank (N. E. Dis. Review) |
| Robert Cowen | Christian Science Monitor |
| Bob Cirroll | WBZ-TV |

LIST OF CONFERENCE ATTENDEES (Continued)

| | |
|--------------------|-------------------------|
| Gen. Irvine | USAF |
| Gen. Bergquist | USAF |
| Gen. McCormack | MIT |
| W. M. Webster | AMC |
| J. F. Reintjes | MIT |
| C. B. Perry | Douglas Aircraft |
| D. T. Ross | MIT |
| F. M. Verzuh | MIT Computation Center |
| O. Dale Smith | North American Aviation |
| D. F. Clements | MIT |
| Douglas Brown | MIT |
| Col. P. L. Hill | AMC |
| Major Hal Susskind | ADSID |
| Dean Stever | MIT |
| Edward Gleason | MIT |
| Jeff Wylie | MIT |
| George Wood | DSR, MIT |
| F. L. Foster | Pres. Office, MIT |
| Walter Milne | |